

Diagnosis of CAM2 in NWP configuration

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Abstract

The Community Atmospheric Model 2 (CAM2) is run as a short term (1 - 5 days) forecast model initialized with reanalysis data. The intent is to reveal model deficiencies before complex interactions obscure the true error sources. Integrations are carried out for three Atmospheric Radiation Measurement (ARM) Program Intensive Operational Periods (IOP), June/July 1997, April 1997 and March 2000. The ARM data are used to validate the model in detail for the Southern Great Plains (SGP) site for all the periods and in the tropical West Pacific for the March 2000 period. The model errors establish themselves quickly, within 3 days the model has evolved into a state distinctly different from the ARM observations. The summer forecasts evince a systematic error in convective rainfall. This error manifests itself in the temperature and moisture profiles after a single diurnal cycle. The same error characteristics are seen in the March 2000 tropical West Pacific forecasts. The model performs well in the Spring cases at the SGP. Most of the error is manifested during rainy periods. The ARM cloud radar comparison to the model reveals cloud errors which are consistent with the relative humidity profile errors. The cloud errors are similar to those seen in climatological integrations, but the

state variable errors are different. The approach described here will facilitate parameterization experimentation and validation. One way of reducing cloud feedback uncertainty is to make the physical processes behave in the most realistic manner possible. Paradoxically, perhaps the best way to reduce uncertainty in cloud feed back mechanisms is to evaluate the model processes with realistic forcing before such feedbacks have any significant affect.

1. Introduction

In the course of their normal operations numerical weather forecast (NWP) centers compare their forecasts to the observational data on a daily basis. The model developers at the centers have made good use of the information obtained by considering model output and observations. Over the years this activity has contributed to a substantial increase in the skill of present day NWP predictions. Climate models, on the other hand, are commonly validated against various statistics based on the observations. These comparisons have enabled the models to produce quite creditable simulations of the present day statistics of the atmosphere (climate). The complication in diagnosing climate simulations is that the models can achieve a reasonable mean state as the result of compensating errors, which will be impossible to individually identify after months or years of integration.

Merging of these validation exercises by running a climate model in NWP forecast mode could be expected to have some benefit. Confronted with actual weather events, the climate model will reveal possible shortcomings in the simulation of some physical processes. Causes of these misrepresentations of the weather would be difficult to diagnose in a statistical evaluation, but could be made manifest in a NWP setting. Thus NWP offers an avenue for possible improvement in the climate model's simulations of physical processes.

NWP is not a panacea for all the ills in climate simulation, however. There are modes of

interaction of the climate system which will only be realized after months or years and in some instances decades of integration, the short term NWP forecasts cannot address these very important climate components. However, it is not unreasonable to speculate that the accurate depiction of the diurnal cycle and daily weather might contribute to the proper simulation of longer term climate modes. If, for example, the cloud formation in a GCM does not have a sound physical basis, then subsequent studies of cloud feedback in that GCM's climate simulation would not address the root of the observed problems and might actually be misleading. Cloud feedback in a climate simulation is a statistical result reflecting the simulated physical processes at work; if the physical processes are flawed then the statistic has limited value. A major stumbling block in the implementation of using a climate model in operational NWP is the lack of a data assimilation system for the climate model. The initial conditions for NWP forecasts are produced by a rather sophisticated data assimilation process in which the forecast model plays an integral role, Kalnay (2003). These systems are complex and at present it is far from a simple task to replace the native model with a 'foreign' model.

However, the ready availability of analyses from sophisticated data assimilation systems has altered the parameters of the problem. The progress made at the NWP centers permits the production of analyses which are accurate (true to the observations) and, of

particular importance for the current project the analyses are in a dynamically balanced state. A model of sufficient quality is able to ingest these analyses and immediately produce useful forecasts without being plagued by startup noise and artifacts created by initial imbalances. Atmospheric analyses are shared by NWP centers on a regular basis and the respective models can be successfully initialized by these foreign analyses. This permits the centers to assess how much the differences in the atmospheric initial conditions are contributing to the differences seen between the forecasts.

For the purposes of this work the success of this analysis 'transplant' by NWP centers offers a route to harnessing the powerful data assimilation systems of NWP to the problem of refining climate models. In this paper techniques will be presented that are closely modeled on the transplant methods of NWP centers to drive a climate model with analyses from two reanalyses projects the NCEP/DOE, Kanamitsu et al. (2002), and ERA40, Simmons and Gibson (2000).

The goal is not just to produce good forecasts, but more importantly to examine the physical processes of the climate model when it is confronted with a known and realistic atmospheric state. Indeed, once the forecast begins to diverge significantly from the sequence of observed states, it is no longer of interest. The issue of validation data is key to the success of this endeavor, since it is desired to be able to assess variables beyond the

usual state variables of temperature, moisture, and winds. Variables such as precipitation, sensible and latent heat flux, radiative fluxes, and clouds need to be validated in order to measure the success of the model's parameterizations. Although such variables are available from the data base of the reanalyses projects, they are derived from the assimilation model's parameterizations. Comparing a model's output to these data has been criticized as merely an exercise of comparing one model's flawed representation of atmospheric processes to another's.

In response to this data requirement, the Department of Energy's (DOE) Atmospheric Radiation Measurement(ARM) Program, Ackerman and Stokes (2003), was established to furnish the necessary observations to enable the physical processes of atmospheric models to be verified in a detailed manner. At present the bulk of the available ARM measurements are from a site in the Southern Great Plains of the United States with less comprehensive data from sites in the Tropical West Pacific. The procedures described in this paper a specific thrust of a more ambitious DOE program, the Climate Change Prediction Program(CCPP)-ARM Parameterization Testbed(CAPT, <http://www-pcmdi.llnl.gov/capt/>). CAPT is part of the DOE effort to improve climate simulations by addressing shortcomings in the modeling of the basic physical processes at work in the atmosphere.

The structure of the paper is as follows: Sections 2 and 3 describe the model used and

the methods employed to initialize it and to produce the forecasts. The data used for validation (mostly from the ARM data base) are described in section 4. Section 5 presents the model climatological errors for selected variables at the ARM locations. The analyses for the forecasts made for the three time periods determined by the ARM Intensive Observing Periods (IOPs) are presented in section 6. An attempt is made in section 7 to characterize the errors and to attribute these to possible shortcomings of the parameterizations. Possible links between the short term forecast errors and the systematic errors seen in climate simulations by the same model are also discussed. The conclusions in section 8 reflect on future efforts and ways in which this methodology can contribute to better cloud representation in GCMs.

2. CAM2 and CLM2 Models

The model used here is the Community Climate System Model(CCSM) Atmosphere Model, version 2 (CAM2). The model was released in October 2002 and is described by Kiehl and Gent (2004) and Dai and Trenberth (2004). The land component of the system, the CCSM Land Model, version 2 (CLM2), Bonan et al. (2002) has 10 levels below the surface. The sea ice fraction and sea surface temperatures are prescribed using the observed monthly mean data distributed with the model. The model was run in its standard atmospheric con-

figuration of 26 vertical levels and T42 spectral truncation in the horizontal, corresponding to a grid of 64 latitudinal and 128 longitudinal nodes with a grid spacing of about 2.5 degrees of longitude and latitude. The model used in the current experiments is identical in dynamical and physical processes to the publicly released version. Dai and Trenberth (2004) provide a concise overview of the physical parameterizations used in CAM2.

3. Methodology

The central problem to be addressed in this project is the initialization of a climate model using an observed atmospheric state. The two main techniques pursued for the atmospheric model were (1) nudging and (2) direct insertion. Land variables were initialized dynamically using a combination of the two atmospheric techniques.

a. *Nudging*

Details of the nudging procedure are described in the Appendix. Nudging entails adding a forcing term to the model equations that pushes the model integration toward the sequence of observed (reanalysis) states. The method worked quite well and produced a sequence of realistic states from which the model could be started in forecast mode (with the nudging

term then being turned off). The vitiating aspect of nudging is that the states so produced during the course of the integration were sufficiently far removed from the observed state that deficiencies in the parameterizations, identified by comparison to observations, might have a component due to these biases and thus not represent a true shortcoming in the parameterization. The model can produce significant biases in short times (3-6 h) which are comparable to the nudging relaxation time scale and such biases induce a departure from the observed atmosphere in the course of the nudging integration.

b. *Direct Insertion*

The direct insertion technique used here mimics the procedures at operational weather prediction centers whereby weather forecasts are made by initializing the center's model using analysis from another center. This entails a careful but straightforward interpolation of variables from one model's vertical and horizontal coordinates to that of another. The term 'transplant' is used to refer to this methodology. In the normal sequence of NWP operations, the model produces a short term forecast (3-6h) which is then synthesized with all the observational data in the data assimilation procedures (analysis). The resulting analysis is then used for the subsequent forecast and the cycle continues, Kalnay (2003). This sequence is designated as the forecast / analysis cycle , hereafter F/A.

There are two common difficulties with the transplant procedures. The first is accounting for the difference in representation of the earth's topography between the models. The difference can be fairly substantial, so care must be taken to use reasonable extrapolations/truncations in regions of terrain mismatch. The second area of concern deals with the land model. The nature of the variables represented in land models does not permit a straightforward mapping of one model's variables into another. This mapping problem is an area of active research (Dirmeyer et al. (2004)), but as yet no clear solution has emerged. Hence, NWP centers use their own land model initial variables in their transplant experiments.

In the experiments described here, the dynamical atmospheric variables were interpolated from the reanalyses grids to the CAM2 grid using methods closely modeled after the ECMWF 'Full-pos' procedures for the Integrated Forecast System (IFS), White (2002). These procedures involve a slightly different interpolation method for each of the dynamic state variables temperature, winds, specific humidity and surface pressure along with careful adjustments to account for the topographical differences between the reanalyses and CAM models. Some judicious smoothing is required to remove artificial gradients, which are especially evident when going from a finer to a coarser grid. The smoothing was accomplished using a spherical harmonic technique consistent with the CAM2 T42

truncation, Sardeshmukh and Hoskins (1984). The procedures are designed to enable the interpolated data to retain dynamic balance, and thus facilitate a smooth model initialization. These methods are used by the ECMWF in their transplant experiments and explicitly account for differences in the underlying topography in a dynamically consistent fashion. The resulting initial state allowed the model to start smoothly without notable oscillations in surface pressure, and the rainfall patterns established realistic values within the first 3 hours of integration.

c. Land Initialization

Proper initialization of the land model is a significant concern to this study. While the atmospheric state parameters provided by the reanalyses can be used with confidence, there is no analogous source of data for the soil variables. The detailed nature of the soil types and their aggregation in a CAM gridbox make it very difficult to use observations in a manner consistent with the model. The only clear course is to spin up the land as described below.

To generate land surface initial conditions for the CAM a three step process was used:

(1) Produce a climatological seasonal land data set by running the model for about ten years using climatological SSTs. The output from this long run is used to generate a land clima-

tological data set for each of the 12 calendar months, (2) Run the CAM2 in a nudging(see appendix) mode for about six months starting from the climatology of the first step, (3) Run the model in the Forecast /Analysis mode for a short period (two weeks) preceding the time of interest to insure that at least the upper layers of the land model are in balance. The second and third steps produce soil moisture in the upper levels consistent with the observed atmospheric evolution. The first step provides deep soil moisture values consistent with the coupled land-atmosphere model. These deep values evolve slowly and have little effect on the surface fluxes for the duration of a short forecast.

Because starting and stopping the CAM2 in the F/A system uses computer resources inefficiently the nudging mode was used in step two, since the nudging proceeds uninterrupted with only some extra input which affects the execution time in a minor way. It should be noted that the initialization procedure outlined above makes no attempt to correct biases in the land simulation. Even if the atmospheric forcing of the land were to follow the observed weather exactly, the model would still produce a land state reflecting the shortcomings of the land model.

d. Initialization Data

Both the ERA40 and NCEP/DOE reanalyses were used to generate the atmospheric initialization data. Both data sets were available on their native grids (vertical and horizontal) which were used by the respective assimilation models. The ERA40 data consisted of 60 model hybrid sigma levels on a Gaussian grid with 180 meridional and 360 zonal Gaussian nodes. The ERA-40 project is described Simmons and Gibson (2000). The NCEP-DOE reanalysis data were generated at 28 sigma levels with 94 meridional and 192 zonal Gaussian nodes. The NCEP-DOE reanalysis is described in Kanamitsu et al. (2002). The results discussed here are based on the integrations initialized with the ERA40 data, since in general these data produced slightly better forecasts than those using the NCEP/DOE , Phillips et al. (2004). Williamson et al. (2004) includes some discussion of the effects of the different reanalyses upon the behavior of the model's parameterizations.

4. Validation Data**a. Atmospheric Radiation Measurement Program**

A critical aspect of the current work is to evaluate the results from the climate model's parameterizations during a short term forecast. Considerable care was taken to ensure

that the model started from as realistic a state as possible so that the subsequent evolution of the model would produce realistic physical processes. A long-standing problem is to have sufficient data available to evaluate the model processes including observations of radiation, clouds, precipitation, diabatic heating rates, and etc.. The DOE ARM program was designed to address these important data gaps. The ARM data and the ERA40 data are generated from largely independent sources, and thus ARM can provide an objective appraisal of the forecasts.

For the Southern Great Plains (SGP) site, the ARM data archive provides a unique, comprehensive data collection. The ARM SGP central site is located at 36.61N, 97.49W and encompasses an instrumented area approximately 3 x 3 degrees in area. Figure 1 shows the location and arrangement of this facility.

ARM provides a 3h time resolution for the upper air parameters and higher frequency for the surface variables. In addition, the Arkansas-Red Basin River Forecast Center (ABRFC) 4-km, rain gauge adjusted WSR-88D radar measurements provide accurate hourly estimates of precipitation over the entire ARM SGP domain. The Surface Meteorological Observation Stations (SMOS) and the Oklahoma (OK) and Kansas mesonet stations provide measurements of precipitation, wind, temperature, humidity, sensible and latent heat fluxes and broadband net radiative flux. The Soil Water And Temperature System

(SWATS), installed at twenty one of the SMOS sites, is designed to provide information about the temperature of the soil and the status of water in the soil profile. Sensors installed at various depths below the soil surface provide hourly measurements of soil temperature and estimates of soil-water potential and volumetric water content. Satellite measurements from the Geostationary Operational Environment Satellite (GOES) provide estimates of clouds and top-of-atmosphere broadband radiative fluxes.

These measurements are combined using a variational technique with the vertical profiles of temperature, water vapor mixing ratio, and winds measured from 3h rawinsondes from the five ARM sounding stations and hourly winds taken by seven NOAA wind profiler stations. The variational analysis uses the SGP domain-averaged surface and top-of-atmosphere (TOA) fluxes as the constraints to adjust the balloon soundings and profiler data to conserve column-integrated mass, moisture, static energy, and momentum. The resulting balanced profiles are available every 3h along with estimates of the heating and moistening rates Q_1 and Q_2 , respectively. The variational analysis of the ARM surface, upper air and satellite observations is described in detail by Zhang et al. (2001). The ARM Millimeter Microwave Cloud Radar (MMCR) and Micropulse Lidar provide high frequency continuous measurements of clouds. A value-added product using the MMCR data is the Active Remote Sensing of Clouds (ARSCL). ARSCL algorithms allow the ge-

ometric extent (in the vertical) of clouds to be mapped and provides information on the size distribution of the cloud particles. The radar is upward-pointing and only samples a narrow vertical beam; thus it cannot provide information on cloud-cover extent over the entire ARM region. Hence, there is a model-observational data mismatch, in that the radar provides highly detailed time information at a point while the model provides information that is intrinsically spread over a gridbox. Radar therefore can miss the presence of clouds of less the 100 percent coverage over a model gridbox.

This issue is addressed in a comparison with the ECMWF forecast model by Mace et al. (1998). They found that by using sufficiently time-averaged radar data there is a enough time/space correspondence to make the radar data useful in diagnosing the model's cloud scheme. In this study, the radar data are averaged over 3h and a scoring method that is based on the presence of cloud rather than the specific cloud amount is used, following Mace et al. (1998).

ARM Tropical West Pacific Data from the ARM site in the Tropical West Pacific(TWP) were also used to validate the model forecasts. Data were available from two sites, Manus (2.058S, 147.425E) and Nauru (0.5S, 167E), Figure 2. The TWP data covered the period of March 2000, but were less comprehensive than the SGP, only encompassing surface measurements and the ARSCL cloud estimates. No upper-air measurements were available.

b. *Global Precipitation Climatology Project (GPCP)*

The ARM data provide comprehensive measurements at specific sites, but for global verification of rainfall the GPCP global daily precipitation were used. These data combine satellite estimates and gauge observations to produce a daily estimate on a 1 x 1 degree grid, Huffman et al. (1997). The GPCP data do not allow insight into the diurnal cycle as do the ARM measurements, but the global aspect of the data sheds light on some larger-scale model biases. The GPCP data suffer from the fact that over water they consist of estimates made from satellite measurements, with all their concomitant uncertainties.

5. Climatological errors in CAM2 at ARM sites

The motivation of CAPT is to put into place tools for identifying deficiencies in the physical parameterizations of climate models. In this section, systematic errors of climate simulations of the CAM2 will be identified at ARM observing sites. Variables chosen for this analysis will be those related to clouds in the model and that also are available in the ARM database. Figure 3 displays profiles of differences between CAM simulations and the ERA40 and NCEP/DOE reanalyses at the ARM SGP site. The months chosen for comparison are the same as the ARM IOPs. Only the June data are shown in this and the

subsequent figure since the June and July results were quite similar and presenting both needlessly complicated the presentation. The AMIP simulation used observed SSTs for the years 1979 to 1995. The CLIMO integration used climatological SSTs and the data is from years 10 to 29 of this simulation. An indication of the robustness of the error across independent realizations of the model is provided by the AMIP-CLIMO differences, which are generally small at the SGP site. There also is good agreement between the ERA40 and NCEP/DOE reanalyses. The consistency of the error for each variable across the different months is particularly striking. It might be expected that March and April would be similar, but the June (and July, not shown) curves have a similar structure to the Spring errors, although there is some indication that the June error has a larger amplitude than the Spring.

Figure 4 is the same as Fig. 3 except that it pertains to March at the TWP ARM sites, Manus and Nauru. The model errors in the TWP are generally smaller in magnitude than at the SGP site. The prescribed SSTs at these ocean site constrain the model, at the SGP site the land may evolve away from the observed state and thus contribute an additional error source. Since the TWP sites are in a region that is directly affected by El Nino variations, the AMIP -CLIMO differences are large. It therefore is logical to use the AMIP as a measure of error since this simulation included observed SSTs. The temperature differences appear to be the opposite of those at the mid-latitude site, with the two reanalyses showing

fair agreement. For the moisture parameters, the reanalyses diverge; the lack of agreement is most manifest in the relative humidity. Few in situ observations are available in this region so differences in assimilation of satellite data and assimilation model biases take on greater significance, producing differences in the reanalyses. The most consistent signal is a pronounced positive bias in the CAM2 relative humidity at the levels above 500 hPa, which is especially large relative to the NCEP/DOE reanalysis.

Comparisons of the low, middle and high cloud fractions between the CAM23 simulations and the observations are presented in Figs 5 and 6. The verification data come from two sources: the International Satellite Cloud Climatology (ISCCP), Rossow et al. (1996) and the land-based observational cloud climatology atlas (ATLAS) of Hahn and Warren (2002). These two data sets are complementary: Land observations are more reliable for the low clouds while the satellite data might have the advantage in observing the high clouds. The Hahn and Warren data provide seasonal means (March, April, May) and (June, July, August) for the low and middle cloud, but provide means for individual months for the high cloud. At the SGP site, the errors are similar across the Spring and Summer; the model underestimates low cloud and overestimates high cloud. This is especially true if the ATLAS data are used for the lower cloud and ISCCP for the highest. Middle clouds, however, do not display an egregious error. This consistency is not too surprising given the

relative humidity curves in Fig. 3 since the cloud fraction in CAM2 is diagnosed using the relative humidity as the key parameter. Over the TWP site, Fig. 6, the glaring error is in the overestimate of high clouds, although there is some indication of an underestimate in the low and middle cloud amount at Manus. Again, this is consistent with the relative humidity bias.

The challenge is to find the deficiencies in the physical parameterizations that contribute to the systematic errors seen in Figs. 3 to 6. There is no reason to expect that the errors in a short-term forecast (1-5 days) should necessarily resemble those in Figs. 3 to 6. As the climatological simulation proceeds, the deficiencies in the various physical parameterizations interact in complex ways, such that the long term error may bear little resemblance to its root cause. Indeed, during the first five days of a simulation, radiation plays only a minor role in forcing variability, but over the longer term its effects can be paramount. Yet, consideration of data such as that shown in Figs. 3 - 6 is valuable in suggesting a starting point as to what aspects of the forecast to examine for the source of systematic error, and as a baseline for assessing future improvements in the climate simulation.

6. Forecast errors in CAM2 at ARM sites

Three time periods that are determined by the ARM IOPs shown in Table 1 are examined in detail. Use of IOP data especially the results of the variational analysis using high frequency (3h) upper air observations at the SGP site provides a great deal of supplementary verification information. The emphasis of this study is on errors that are averaged over the first 24 hours of the forecast over a number of forecasts. This is an effort to characterize the systematic errors that might be expected to impact a climate simulation, rather than just a specific forecast failure. Such averaging however prevents study of the diurnal cycle. A follow on work will address some aspects of diurnal variation in column budgets, Williamson et al. (2004).

a. *June / July 1997 IOP - 18 June 1997 to 17 July 1997*

Synoptic Maps Before focussing on the details of the integrations at the SGP site, some synoptic maps are shown to demonstrate the performance of the model on larger scales over the continental US. These charts indicate that the model forecasts the the overall synoptic situation such that the parmeterizations are forced in a manner consistent with observations. The model performance in forecasting the 500 hPa height field on the hemispheric scale is

very credible if the mean anomaly correlation used as a metric, Phillips et al. (2004). Figure 7 shows the MSLP, lowest model level winds, precipitation, and total cloud cover for a 24 hour forecast of the model valid at 4 July 00Z 1997. A surface observations chart is given in Fig. 8. This one day is an illustrative example typical of all the forecasts. The pressure field shows that the forecast does quite well in depicting the location and strength of the pertinent systems. The wind field displays a similar fidelity to the observations, and the wind shifts also indicate that the frontal positions are accurate. The rainfall cannot match the radar exactly since the model output is a 3h average over the period ending at 00Z, while the radar estimates are instantaneous. For the most part the rain does line up with centers of observed activity, but an exception should be noted over the southern part of the Gulf Coast states. The cloud cover is fairly well handled although the model incorrectly puts cloud over the southeast US. This anomalous cloud is for the most part high cloud.

Figure 9 displays the daily mean global precipitation rate for 4 July 1997 from the GPCP daily estimates (top) and the model forecast (bottom) starting from 3 July 1997 12Z and averaged over 4 July. Although for a single day, the plot shows characteristics that the model exhibits on a systematic basis. The model does better in the winter (Southern) Hemisphere in predicting the intensity and location of the precipitation events. In the Tropics and summer midlatitudes, the model does only a fair job on location and usually

underestimates intensity. Note there is very light precipitation over the south east US, which is coincident with the cloud and precipitation error noted above. There is a global tendency in convective regimes to produce broad regions of light precipitation that do not correspond to the GPCP estimates. These same characteristics of persistent, light precipitation and accompanying clouds in convective regions are evident in the detailed measurements from the ARM sites.

Precipitation Figure 10 shows the time series of precipitation at the SGP site during June/July 1997 for a series of model 24h forecasts initiated every six hours and observations from ARM. The values plotted are six hour averages for the last 6h of the 24h forecast. The results using the same sampling for 12h and 18h forecasts are similar. It is clear that the model rains nearly every day and fails to capture the episodic nature of the rain events seen in the observations. This behavior may be associated with deep convection in the model which is parameterized using the Zhang-McFarlane(ZM, Zhang and McFarlane (1995)) scheme. since a similar pattern producing daily rainfall over the US Great Plains has been observed using the ZM scheme in other contexts, Xie and Coauthors (2002), Dai et al. (1999). Table 2 presents the joint distribution, Wilks (1995), of the ARM observations and the model's 24h forecasts of precipitation. The marginal distributions of the forecasts show the ubiquity of the rainfall events in the model. In the model's defense, the frequency

of predicted rain might be an artifact of the four grid cells that are used to generate the CAM estimates (see Fig. 1) at the SGP site. These grid boxes occupy a larger area than the SGP region, and thus the model might be depicting actual rain events that are not encompassed by the ARM region. However, there are radar estimates of precipitation from ARM (ABFRC), calibrated with rain gauge data at the SWATS locations, which extend over the full CAM grid cells. In Fig. 10, the average of these radar values over the larger region indicate that the rain events do indeed occur more often. Comparison of the CAM and radar time series indicates that the model nonetheless overestimates the frequency of precipitation. Averaging over the larger area also diminishes the magnitude of the peaks in the rain events, but here again the model is unable to match the reduced peaks of the radar data.

SGP column The rainfall is the result of many processes at work in the atmospheric column. The ARM SGP IOP data permit a further investigation of the evolution of the variables above the SGP. Figure 11 displays the error in relative humidity for a sequence of 24 hour forecasts initiated every 6h from 18 Jun 97 to 17 July 97 at the SGP. The error is defined as the model estimate less the ARM observed values. The persistence of the error through most of the time period is noteworthy. The evolution of the difference in the model and ARM relative humidity is shown in Fig. 12. The figure shows the mean difference in

the relative humidity between 5 day model forecasts initiated at 00Z and ARM. The errors are established within the first 24h and then level off to a roughly steady state. The diurnal pulses of differences are apparent in the figure as the convective processes are triggered each day in the early afternoon. The low level drying is established in the first 24 hours and only slightly increases for the next 4 days. For this variable, the model forecasts an atmospheric state significantly different from that observed after two days. Figure 13 shows the mean 24h forecast error in temperature, specific humidity and relative humidity for June/July 1997 at the SGP site. The model is too moist both above 500 hPa and in the boundary layer, and too dry between 500-900 hPa. The model data indicate that the lower tropospheric drying appears to be primarily due to the ZM deep convection scheme while the upper level moistening is from evaporation of rainfall primarily by ZM, Williamson et al. (2004). An examination of the time evolution indicates that a large contribution to the error comes in the 9AM to 3PM LST time frame, consistent with convective sources and, an error which is also noted by Dai and Trenberth (2004). Column temperature errors indicate that the model is much too warm in the upper troposphere between 200 and 600 hPa, too cold near the surface in the boundary layer and a bit warm between 900 and 600 hPa. The time evolution of the errors is similar to that of the relative humidity, Fig. 12, in that the errors establish themselves early in the forecast. The warming appears to

be probably due to the ZM scheme. As indicated by Dai and Trenberth (2004), the ZM scheme implemented in the CAM2 is triggered too often and too early in the day during summer. The scheme appears to be overly sensitive to CAPE formation and proceeds with the convective processes without due regard for inhibitory aspects of the synoptic situation, Xie et al. (2004).

SGP-surface Table 3 lists the 24h forecast errors for the surface sensible and latent heat fluxes over the SGP region, and shows that the sensible heating is consistently too small and the latent heating is consistently too large. These fluxes are consistent with the atmospheric temperature and moisture errors in the boundary layer, if they are considered as a source of the latter anomalies. The special rawinsonde data allow for an estimate of the PBL height at the SGP region, Delle Monache et al. (2004). Figure 14 shows that the model consistently underestimates the PBL height at the SGP site by a large factor. The model also does not display as much diurnal variation, the daytime maximum being greatly underestimated by the model. The very steep gradient below 900 hPa in the specific humidity of Fig. 13 may indicate that the PBL transfer is not deep or efficient enough. The model's PBL depth would also be adversely affected by the deep convection occurring too frequently and too early in the day. The results of the April 1997 case, discussed below, indicate that the ubiquitous rainfall may inhibit the vertical growth of the PBL height in the model.

SGP/Soil Temperature and Moisture As mentioned in Section 3c, proper initialization of the soil model is a significant concern to this project. There can be a fair amount of confidence in the atmospheric state parameters provided by the reanalyses, but there is no analogous source of data for the soil variables. The detailed nature of the soil types and the nature of the soil type aggregation in CAM gridbox make any use of observations problematical in view of the large variation of soil types, landforms and land use across the ARM site, Luo et al. (2003). Thus, model-observation comparisons of soil moisture and temperature are necessarily qualitative and are presented to provide some indication of the ability to achieve a reasonable initial state in the land model.

Because soil moisture in the uppermost layers (5cm) has the most impact on the short term forecasts, the top layer of the SWATS temperature and volumetric soil moisture data (at 5 cm depth) are compared to the 24 hour forecasts of the land model's top 3 soil layers (0.71, 2.8, and 6.2 cm) in Figure 15. Given the substantial uncertainty in these types of comparisons, the model-observed differences are not too large. The model land initialization (see Section 3c) seems to have generated a reasonable land state but in general the soil is a little too dry and warm. In light of the lower-level errors in atmospheric temperature and in the surface sensible and latent heat fluxes, the surface-atmosphere exchange formulation in CAM2 might need attention. The lower atmosphere is too cold, the sensible heat flux is

too small, and yet the land is still too warm. On the other hand the latent heat fluxes are too large which is consistent with the land drying and the atmosphere moistening. This is consistent with the differences between the observations and initial conditions. The relation between the observed and land model variables change very little from the initial state over the duration of the 24h forecast.

Clouds Figure 16 presents the comparison of the ARSCL product to the model cloud for 24h forecasts across the IOP. The most obvious difference is in the low / middle cloud from 900 to 500 hPa where the model appears to systematically underestimate cloud amount. There is too much high cloud in the upper levels. The increased vertical resolution afforded by the radar does show that the traditional low(surface to 700 hPa), middle (700-400 hPa) and high (above 400 hPa) categories of cloud levels would mix together distinctly different types of model errors. This is especially true of the 700 to 400 hPa region. Aggregating the cloud fractions from the model levels through this layer could produce a conclusion somewhat different from that gathered from Fig 16. The very lowest levels (below 900 hPa) are not suitable for detailed comparison because the radar signal can be compromised by other aerosols (e.g. dust, insects) in the layer, Mace et al. (1998). Except for marine stratus, cloud fraction in CAM2 is diagnosed using a scheme that involves relative humidity as a key variable. It is thus not surprising that the cloud error follows the relative humidity

error in Fig. 13.

b. April 1997 IOP - 2 April 1997 to 23 April 1997

Synoptic maps representative of this period are not presented. The model performs significantly better in April compared to June /July, and the point of the previous figures would only be re-iterated. The model provides a very credible short term forecast.

Precipitation Figure 17 presents the 24h forecast and observed precipitation for the period 2 April to 23 April 1997. There is a marked improvement over the performance in the summer case, Fig. 10. The model captures the episodic nature of the rain quite well but under-predicts intensity. The radar data indicate that this reduced rain intensity is at least in part due to the larger area encompassed by the four CAM2 grid boxes. Table 5 also indicates the general improvement over the summer case. The model success in discriminating between precipitation regimes allows a partitioning of the data into rainy and clear periods in the subsequent analysis. "Rainy" denotes those times when both the model and observations show rainfall, and "clear" when both show no rainfall.

SGP Column Figure 13 (center panels) displays the mean 24-hour error in temperature, specific humidity and relative humidity at the SGP site for the April 1997 IOP during rainy

and clear periods. The figure shows that the rainy periods generally contribute to the bulk of the error for the chosen variables. The model is too warm and too moist below 700 hPa and the warm bias is larger for the rainy periods. The rainy relative humidity pattern is not unlike that of the June/July 1997, but the profiles of temperature and moisture for the two cases are quite different. The terms of the atmospheric moisture budget, (Williamson et al. (2004)), indicate that the moist processes are not removing enough moisture in the lower layers to offset the vertical diffusion.

In April the contribution of the ZM deep convective scheme is secondary to the shallow convective parameterization of the model, Hack (1994). Figure 18 shows that the model does much better overall in predicting the PBL height in April 1997 than in June/July 1997, Fig. 14. The beginning and end of the period show larger discrepancies in which the model underestimates the PBL height. It is during these periods that the model is producing light rainfall that is not observed, a feature consistent with the June/July 1997 results when the near constant rain was coincident with an underestimate of PBL height.

SGP-surface The surface sensible and latent heat errors shown in Table 3 for April 1997 are much like those of the June/July 1997 for the rainy periods, but they change sign for the dry periods. Thus, the sign of the flux errors is consistently tied to occurrences of rain in both cases. The fact that flux errors reverse sign indicates that the model's treatment of

rain is not the only determinant of surface flux errors.

SGP/SWATS Figure 19 compares the SWATS upper layer soil temperature and moisture data to the 24 hour CAM2 forecasts for April 1997. The model soil is distinctly drier than the observations and evinces somewhat more variability. The model shows rapid increases of soil moisture during rain events and a steeper drying over the nearly rainless second half of April. As in the summer case, the short term forecasts largely carry the biases seen in the initial land with only minor changes. The model soil is systematically warmer than the observations, with maximum differences approaching 8 C. The model appears to do a good job in following the slow changes in the soil temperature despite the large bias. The CLM2 model used in CAM has a documented warm bias during the cold season in high and midlatitudes, Kiehl and Gent (2004). As in the summer case, however, it is difficult to depict a consistent picture of the error in the soil, surface fluxes and lowest level atmospheric temperature and moisture.

Clouds Figure 20 presents the ARSCL cloud forecast comparison for April 1997. The clouds track the transition from a rainy to dry period around 13 April. Before this time, the model does well in predicting cloud, and afterward it does well in simulating clear regions. In both periods the most consistent tendency is for the model to miss low/middle clouds,

and overall the systematic error is too underpredict clouds. The association of relative humidity and cloud errors is not as clear cut as in June/July 1997, although the underestimated low level relative humidity is coincident with the reduced low/middle cloud.

c. March 2000 IOP - 1 March 2000 to 22 March 2000

For the March 2000 IOP the results at the SGP site resemble those for April 1997, and so this case will be described in less detail. Instead, the novel aspects of this IOP related to the availability of observations at the TWP site will be emphasized.

Precipitation The time series of 24h forecasts and observations of precipitation at the SGP are shown in Fig. 21. It is seen that there was a sequence of rain events approximately evenly spaced throughout the March 2000. As shown in Table 6, the model does as well in depicting the sequence of rain events. This allows a similar partitioning into dry and rainy periods as was done for April 1997.

SGP column The temperature and moisture error profiles for this IOP, shown in Fig. 13(rightmost column), are strikingly similar to those of April 1997. This gives some evidence that a robust climatology of short term forecast error can be established and that the more subtle aspects of parameterization diagnoses can be teased out. A notable difference

is the somewhat larger relative humidity positive bias in the upper levels in March 2000.

SGP Surface As seen in Table 3, the rainy surface fluxes in March 2000 exhibit a similar error sign to those of April 1997. The dry period has the same negative error in latent heat flux, but the sensible heat flux in March 2000 is strongly negative, while it was positive in April 1997. Thus there is not a simple rain versus no-rain relationship to sensible heat flux biases for the cases in Table 3. More investigation is obviously needed, unfortunately, the SWATS data are not yet available for the March 2000 case.

Clouds at SGP Figure 22 shows the comparison of the ARSCL product and CAM clouds at the SGP site for 24h forecasts for March 2000. The most common model error is to miss the presence of cloud, but there is no clear bias at the upper or lower levels. The model has a slight tendency to overestimate high cloud but this is a modest amount given the size of the relative humidity bias. It appears that when clouds occur the model overestimates the relative humidity, but less so when clouds are absent, or at least not enough to trigger false positives of high cloud.

TWP March 2000 Figures 23 and 24 presents the precipitation time series during the Mar2000 period for the Manus and Nauru ARM sites. In addition to the ARM and CAM data, the daily GPCP values for this location are also displayed. The ARM data are hourly

values, these are averaged to the three hour CAM sampling. The plots show a decrease in precipitation amounts in going eastward from Manus to Nauru for this period. The CAM fails to capture the episodic nature of the rainfall at either location. The CAM rainfall time series at both locations is reminiscent of the June/July 1997 SGP rain time series, a persistent light rain with a diurnal variation. This would indicate that the model error related to modeling convection might not be restricted to locations over land, since the model takes both TWP locations to be virtually all ocean. Fig. 9 shows an example of the model's diffuse light rainfall in the TWP as contrasted to the intense distinct centers estimated by the GPCP. The GPCP data for the two sites indicate that these daily satellite based estimates are poor in capturing the nature of the rainfall at the TWP locations. The ARM data are important in showing that the temporal variation of the CAM rainfall is clearly in error.

TWP column There were no special ARM upper air observations available for the TWP site for March 2000. Figure 25 presents the mean differences between the 24h forecasts and the ERA40 data. There is not a differentiation between clear and rainy since the model rains almost all the time. Interestingly enough, the errors do bear some resemblance to those of June/July 1997 at the SGP site. This gives some evidence of a common origin in the convective parameterization which was active through out June/July 1997. If one

only considers the ERA40 curves, Figures 25 and 4 show some commonality. The forecast error and climatological error thus may have some relation to each other in this region of the Tropics. The tropical sites are both essentially oceanic (from the model's point of view), so some of the commonality in error might originate from the fact that both the climate (AMIP) and forecast simulations are driven by the same SSTs. At the SGP site the land model presents very different states to the climate and forecast integrations and this provides another source of differences. The comparison to the ERA40 data is somewhat suspect since these data were used to initialize the model. However, these differences do provide a measure of the magnitude and direction of the model drift from the initial conditions over the forecast time.

Clouds TWP Figure 26 shows the ARSCL product comparison to the 24 hour cloud forecast at the TWP sites. At Manus the model systematically underestimates the low/middle clouds 800 to 500 hPa, while greatly overestimating the high cloud. At Nauru, the high cloud is overestimated somewhat less. The model also evinces a climatological systematic error in overestimating high cloud in the TWP, as illustrated in Fig. 6. The high-cloud overestimate is consistent with the relative humidity biases in Fig. 25.

7. Discussion

a. relation to AMIP climatological errors

Comparing the figures for the CAM climatological errors, Figs. 3 and 4, and the 24h forecast errors, Figs. 13 and 25, there is little correspondence between climate and forecast errors except for the relative humidity. The pattern of overestimating humidity at upper levels, and underestimating it at lower levels is seen across all the cases. However, the corresponding temperature and specific humidity profiles are somewhat more disparate. For example, in Fig. 3 climatological relative humidity error for June is driven by the temperature profile while the forecast error for June/July 1997 in Fig. 13 is mainly due to the specific humidity.

Thus, there is a similarity in the relative humidity error for climatology and forecasts, but the etiology of the respective errors is distinct. This result is not at all surprising. Figure 12 demonstrates that the relative humidity grows rapidly within the first five days of integration for the June/July 1997 SGP case. Over a climatological run the state of the atmosphere is thus sufficiently far from a realistic state that the error characteristics would proceed in a different manner than the forecasts. This would imply that attempting to invert the errors seen in the climatological integrations to errors in the physical processes

would be fraught with uncertainty. The goal is to reduce the climatological errors but an important path to this reduction might well be the careful analysis of the short term forecast. The error seen in the June/July 1997 forecasts is very systematic, 11, yet its signature is transmogrified by other interactions so that it is unrecognizable in the climatology.

The foregoing discussion indicates that similar caution must be exercised when considering the model-observational differences in clouds. Figures 5 and 6 show the climatological differences and Figs. 16, 20, 22 and 26 display the forecast comparisons to observations of clouds. There is a fairly good correspondence between the climatology and the forecast errors. The forecast overestimate of high cloud in convective regimes is quite clear as is the underestimate of low cloud at almost all times and locations. This cloud error is consistent with the error in the relative humidity profile. It is not obvious, however that the processes that spawn the high clouds in the first day of the forecast and those that maintain their existence for 15 years of integration are the same. What can be surmised is that there are feedbacks that maintain the high cloud in the climatological sense even after the state of the atmosphere has changed due to other effects not seen in the five day forecasts. It follows that the model might have different paths to the same error pattern, and the close examination of short term errors and some experimentation can reveal the true etiology of the error which is obscured in the climatology. The paradox is that cloud feedback uncertainties can

be usefully addressed before cloud feedback can exert a dominant influence. The short integrations shown here do not have enough time for radiative feedbacks to become effective. Thus, the physical errors can be identified before being entangled in feedbacks, placing the diagnoses of actual feedback loops on firmer ground.

b. *Land and Surface*

An aspect of the current work that has no elegant solution is the initialization of the land. Validation of the land model is important in its own right and the state of the land upper levels will have an impact on the surface exchanges of heat and water. Figures 15 and 19 indicate that the soil is in fair agreement with the observations and does track the time variations at the SGP site. Table 7 summarizes the model and SWATS observations differences. There is apparently a consistent bias in that the model is generally too warm and too dry. Table 3 indicates that despite the land being too warm, the sensible heat flux displays a negative difference with the observations. This negative value is seen even in the June/July 1997 case where the lower atmospheric temperature is too cold. The latent heat flux has a positive bias when it is raining, and a negative bias when it is dry. Thus, it seems that the land biases are not dominating the sense of the surface exchanges. Nonetheless, increasing the accuracy of the land initialization is a prime goal of future work so as to allow a clear

identification of the source of such flux errors.

8. Conclusions

The CAM2 atmospheric model was initialized by state variables from reanalyses and run as a forecast model for short time periods (5 days). The land surface model, CLM2, was spun up by integrations forced by observed state variables for the period preceeding the forecast. The goal is to analyze the model evolution in the short term starting from as realistic conditions as possible, so as to be able to isolate specific shortcomings in the modeling of the physical processes before other interactions obscure the actual error source.

Forecasts were produced for three ARM IOPs, June/July 1997, April 1997 and March 2000. Forecasts were initiated every six hours and the state variables were updated at these times. This sequence mimics the forecast analysis cycle of NWP centers. The experiments indicate that the CAM2 is capable of producing high quality short term forecasts. Detailed validation of the model at the ARM Southern Great Plains and tropical West Pacific sites was carried out. The validation exercise shows systematic errors in convective regimes apparently related to the deep convective parameterization. The error in these regimes is quite systematic and manifests itself over the course of a forecast of a single diurnal cycle. In regimes where only shallow convection is invoked the errors are reduced but the error

during rainfall events is somewhat larger than during clear periods. There are some seeming inconsistencies between the state of the land, the surface air temperature and moisture, and the surface sensible and latent heat fluxes. These might be indicate a shortcomings in the modeling of the surface exchange layer.

The land initialization is an issue. There are global soil data sets available, but there is not yet a consensus on how to map observations to the variables of a specific land model, Dirmeyer et al. (2004). The current land spinup technique appears to be adequate in the sense that it appears that other CAM2 biases are overwhelming the contribution from the land although there is some evidence of persistent biases in the land state .

Future work will involve the next release of the Community Atmospheric model. It is planned to run experiments for much longer periods in the forecast / analysis mode. The longer runs will permit a stratification of the observed conditions and model forecasts so as to a diagnosis of specific parameterizations. In the current work it was not possible to stratify the data according to clear versus cloudy conditions. In the current set of experiments the number of instances that the model and observations agreed with respect to the cloud distribution was very small and insufficient to get definitive results as to the nature of the cloud feedback processes in the model.

A. Nudging

The CAM2 code was modified to permit the solution to be continuously 'nudged' toward a target analysis during the integration of the model. The nudging technique has a rich history, mostly as a model initialization method, Hoke and Anthes (1976). The basic idea is to modify the prognostic equations to include a term that decreases the distance between the predicted value and a target analysis. The values are not forced to exactly match that of the analysis, the degree of conformance is dictated by a relaxation constant. This value is usually expressed in terms of the e-folding time for the model to come into agreement with the analysis, all else being equal. This is depicted in the following equation:

$$\frac{\partial T}{\partial t} = \dots \frac{T - T_A}{\alpha} \quad (1)$$

The value of α was chosen such that the variables would relax to the analysis in 6 hours. The variables so adjusted were the atmospheric prognostic variables: temperature, wind, moisture and surface pressure. The ARM IOPs considered here occurred in 1997 and 2000. For all the cases the CAM was run in the nudging mode from the first of January to the start of the IOP period. Two separate integrations were performed using the R2 and ERA40 data as nudging targets. These same data provided initial conditions for the

subsequent experiments. The reanalysis data were available every 6 hours, and these were interpolated using a cubic polynomial to the 20 min time step of the model. This degree of nonlinearity was determined sufficient to adequately drive the model, after experimenting with interpolation schemes ranging from linear to quintic.

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IOP Designator	Start and End Dates	Duration (Days)
June/July 1997	18June - 17July 1997	30
April 1997	2 April - 23 April 1997	22
March 2000	1March - 22 March 2000	22

Table 1: The dates and designators of the ARM Intensive Observation Periods used in this paper.

		Observed		
		YES	NO	Sum
Model	YES	65	34	99
	NO	0	1	1
	Sum	65	35	66

Table 2: Joint distribution table of 24 hour forecast precipitation at the SGP site for the June/July 1997 IOP

	Sensible Heating (W/m^2)	Latent Heating (W/m^2)
June/July 1997	-12	+26
April 1997 - Rain	-11	+28
April 1997 - Dry	+14	-7
April 1997 - All Days	-3	+15
March 2000 - Rain	-5	+23
March 2000 - Dry	-23	-7
March 2000 - All Days	-12	+10

Table 3: Differences in latent and sensible heat fluxes between ARM observations and 24h CAM forecasts at the SGP site.

	Yes(Radar)	No(Radar)
Yes (Model)	Hit(Green)	False Alarm (Red)
No(Model)	Miss (Blue)	Hit (White)

Table 4: Summary of Model-ARSCL comparison conditions color coding.

		Observed		
		YES	NO	Sum
Model	YES	61	16	76
	NO	3	20	23
	Sum	64	36	81

Table 5: Joint distribution table of 24 hour forecast precipitation at the SGP site for the April 1997 IOP.

		Observed		
		YES	NO	Sum
Model	YES	42	12	54
	NO	7	40	47
	Sum	649	52	82

Table 6: Joint distribution table of 24 hour forecast precipitation at the SGP site for the March 2000 IOP.

	Soil Temperature (K)	Volumetric soil water (mm^3/mm^3)
June/July 1997	2.5	-0.023
April 1997 - Rain	5.7	-0.11
April 1997 - Dry	6.3	-0.12
April 1997 - All Days	6.1	-0.11

Table 7: Differences in soil temperature and moisture estimates between SWATS observations and 24h CAM/CLM forecasts at the SGP site. The values are those of the topmost 5 cm of soil,

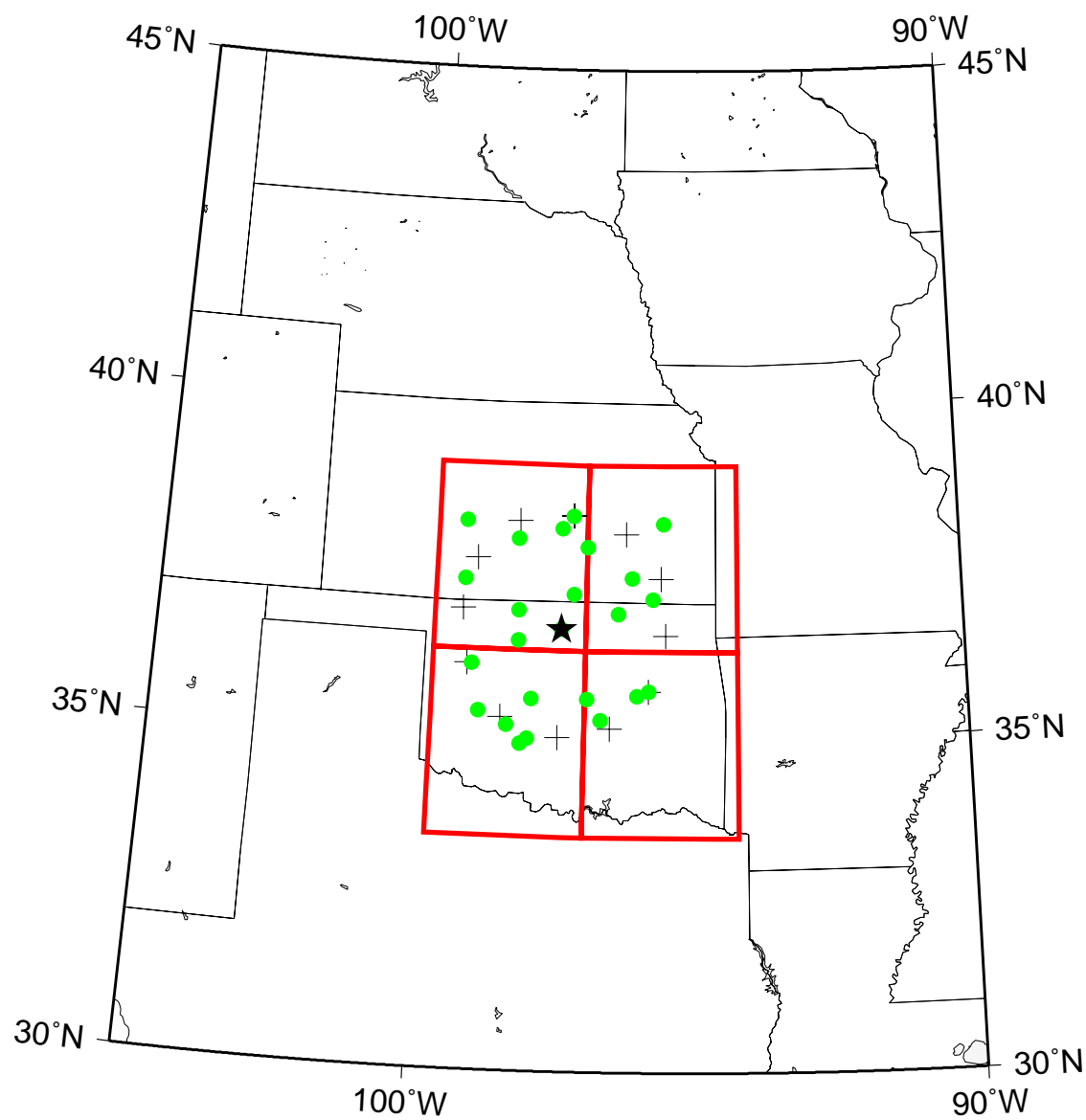


Figure 1: ARM SGP locator map. Green dots are SWATS stations, blue crosses are 3h rawinsonde sites, the red boxes outline the pertinent CAM2 grid boxes.

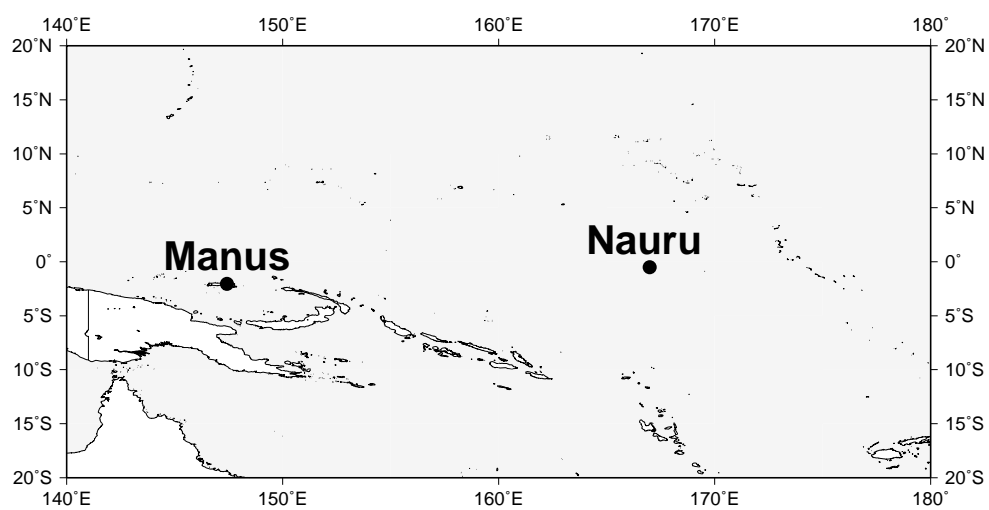


Figure 2: ARM observing sites in the Tropical West Pacific.

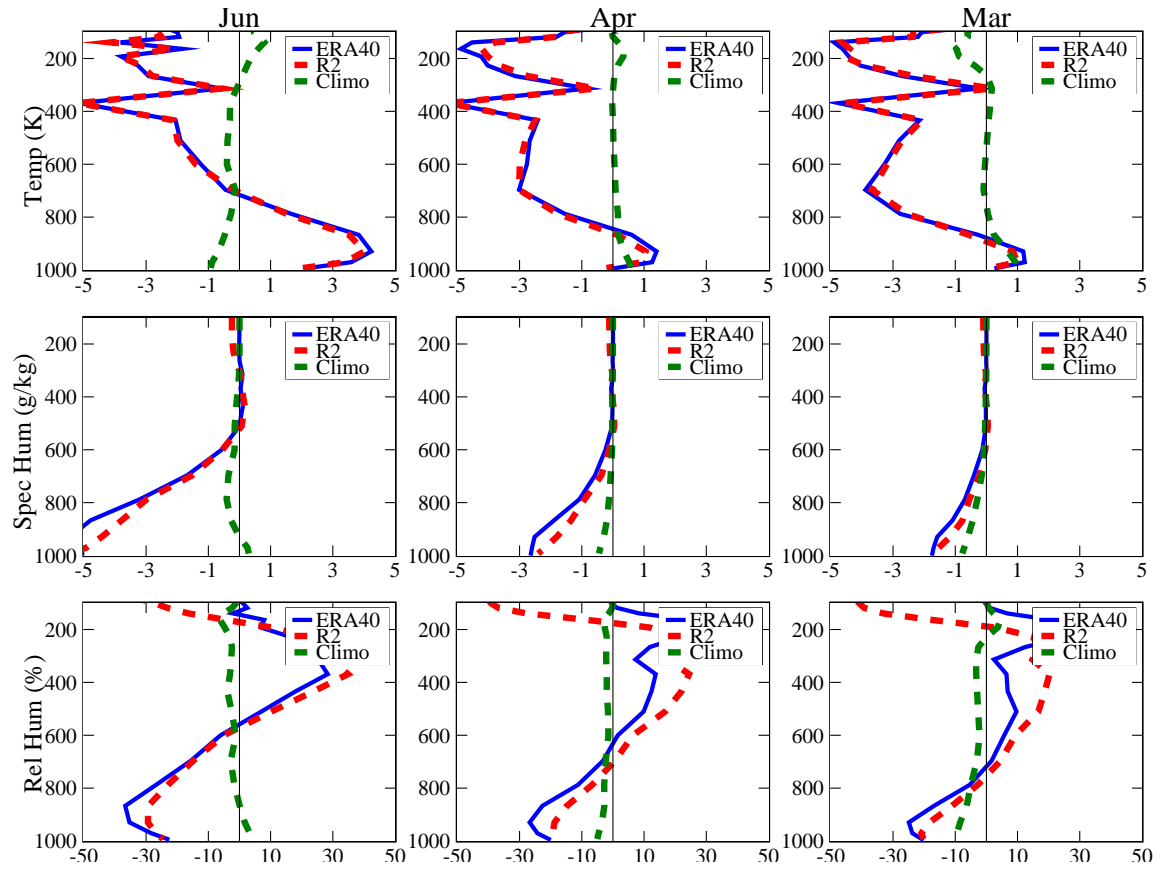


Figure 3: Difference between CAM2 AMIP (79 -95) simulation and ERA40, DOE/NCEP reanalyses and a 15 year simulation using climatological SSTs at the ARM SGP site for temperature(K), specific humidity(gm/kg) and relative humidity(percent). Results are shown for the months of June, April and March.

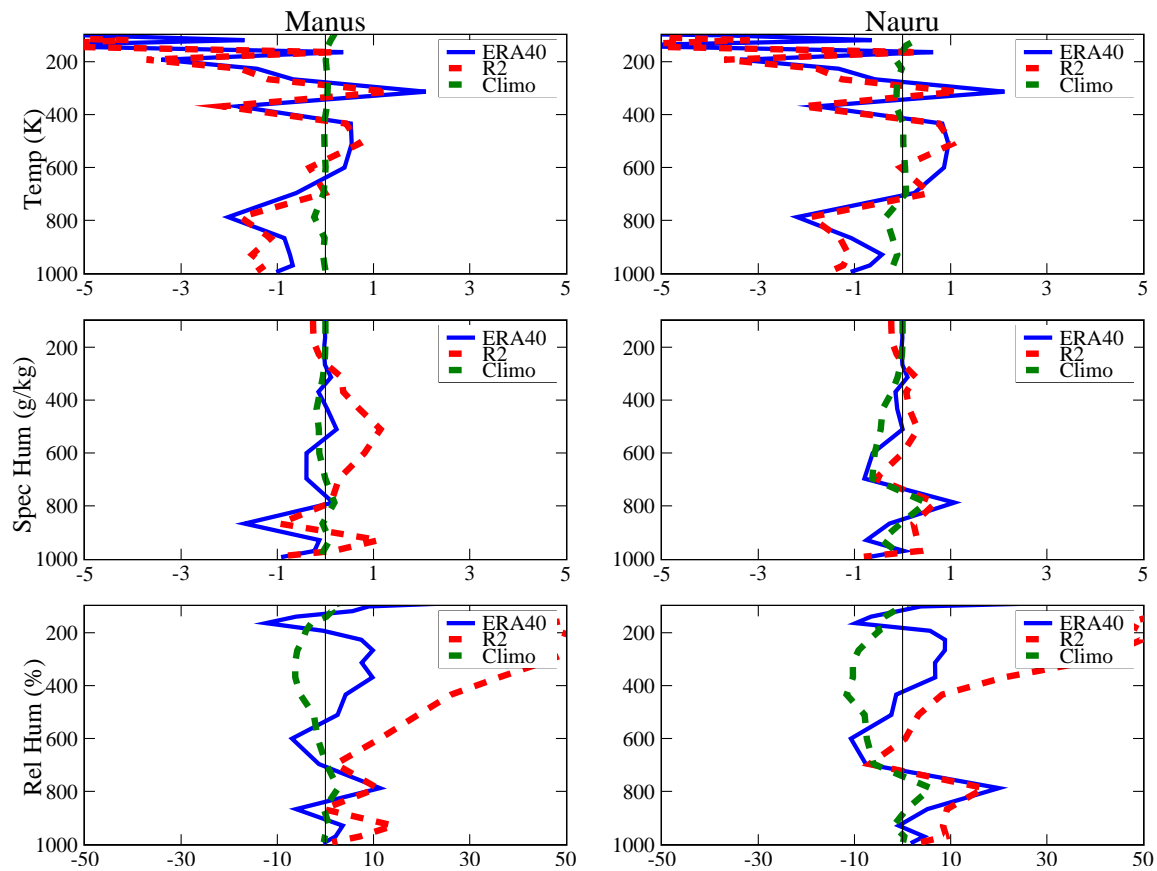


Figure 4: Difference between CAM2 AMIP (79 -95) simulation and ERA40, DOE/NCEP reanalyses and a 15 year simulation using climatological SSTs at the ARM Manus and Nauru sites for temperature (K), specific humidity (gm/kg) and relative humidity (percent). Results are shown for the month of March.

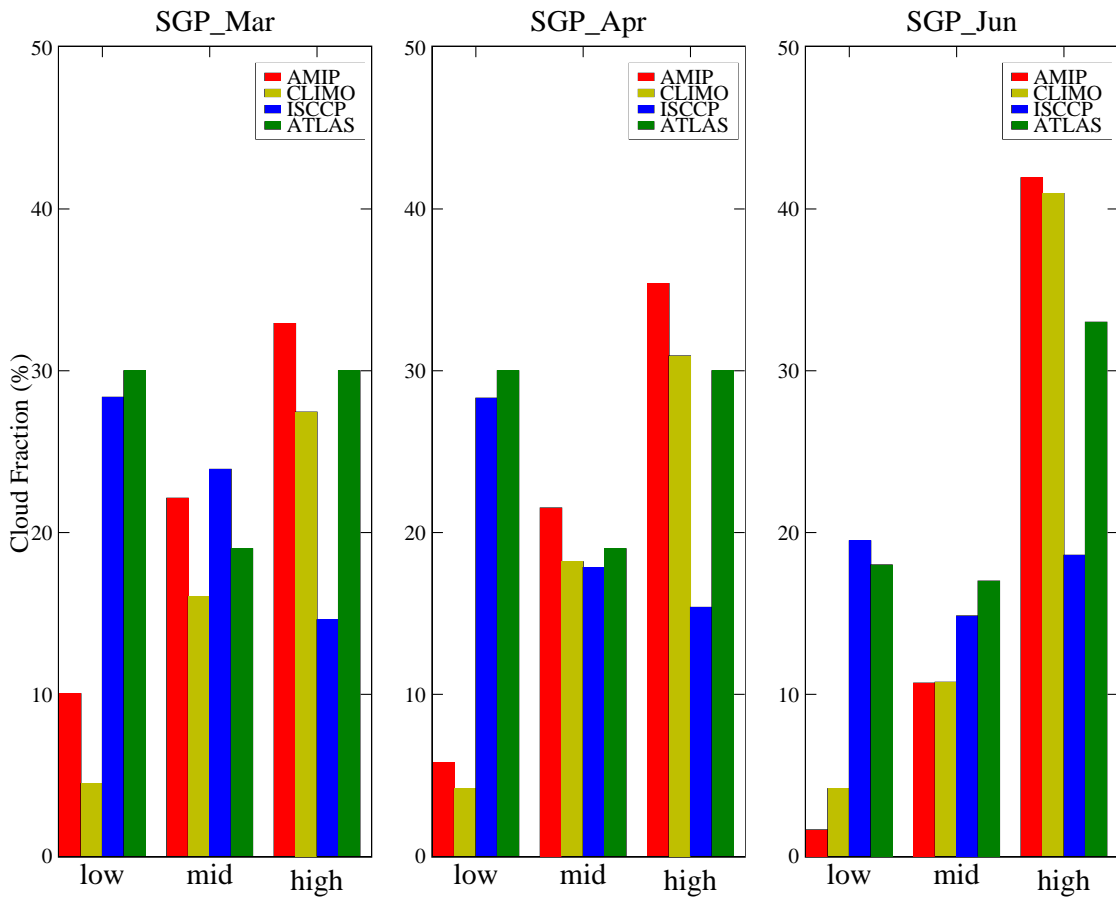


Figure 5: Comparisons of low, middle and high cloud simulated by CAM2 AMIP (79 -95) and a 15 year simulation using climatological SSTs and ISCCP and Cloud Atlas at the ARM SGP site for the months of March, April, June and July.

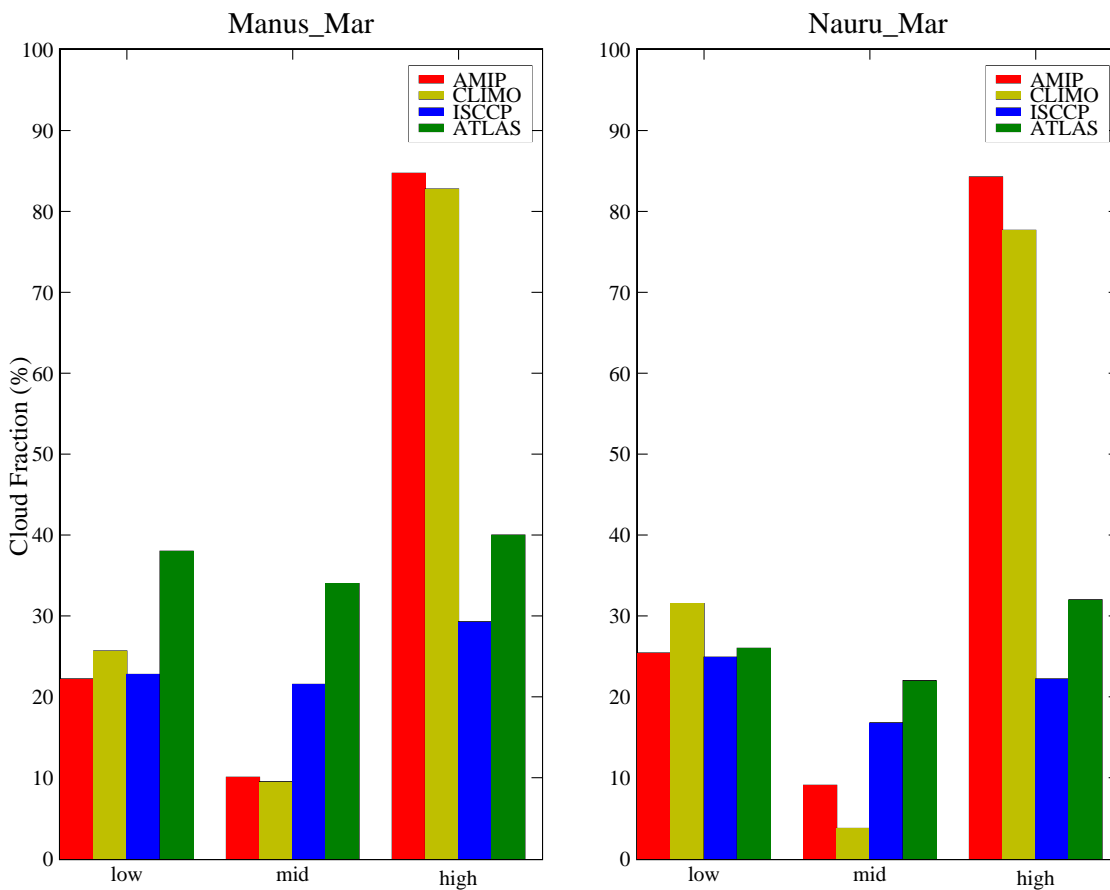


Figure 6: Comparison of low, middle and high cloud simulated by a CAM2 AMIP (79 -95) , a 15 year simulation using climatological SSTs and ISCCP and Cloud Atlas at the ARM Manus and Nauru sites for the month of March.

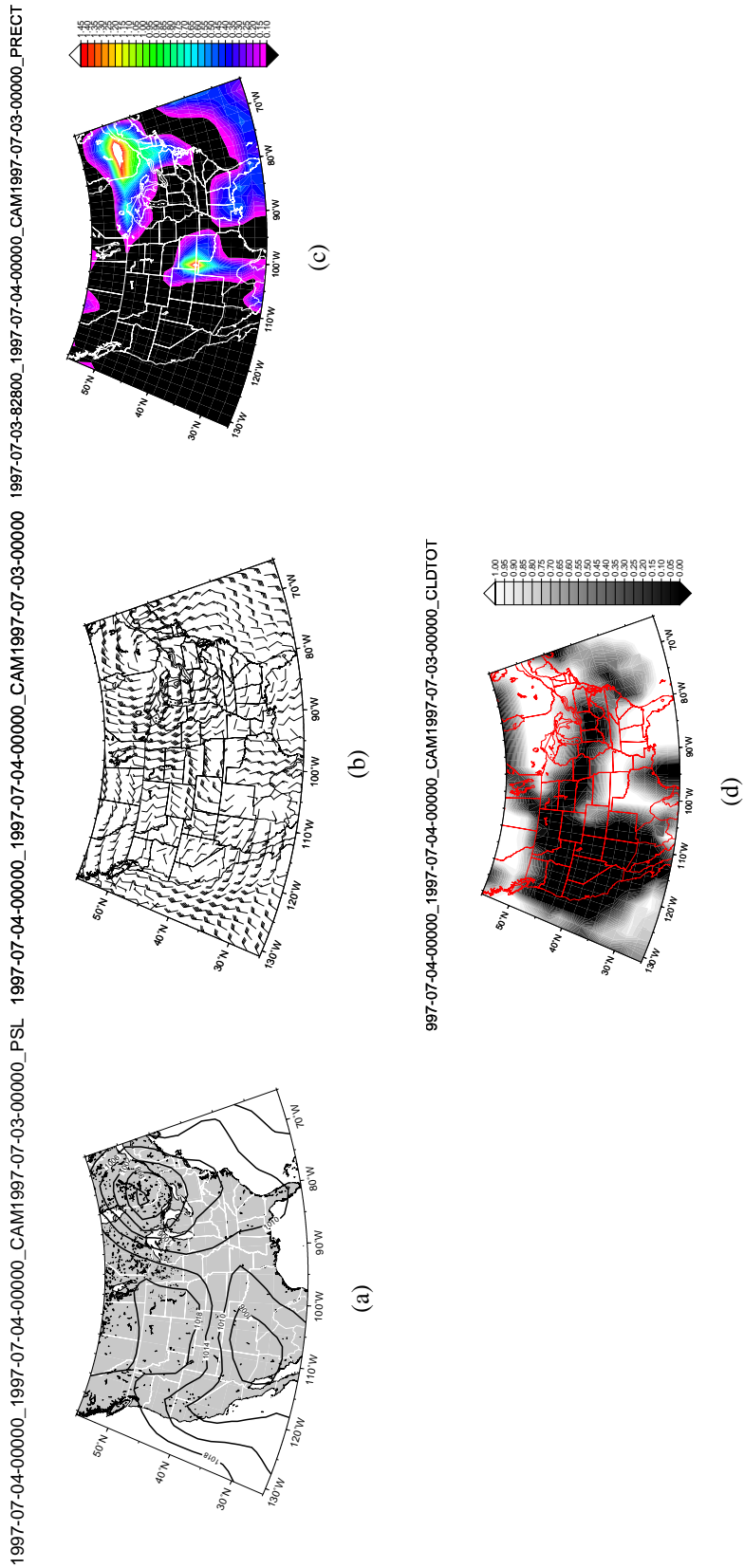


Figure 7: Twenty four hour forecasts valid at 00Z 4 July 1997 of (a) sea level pressure (hPa), (b) lowest level wind (m/s), (c) precipitation (mm/h) and (d) total cloud cover (%).

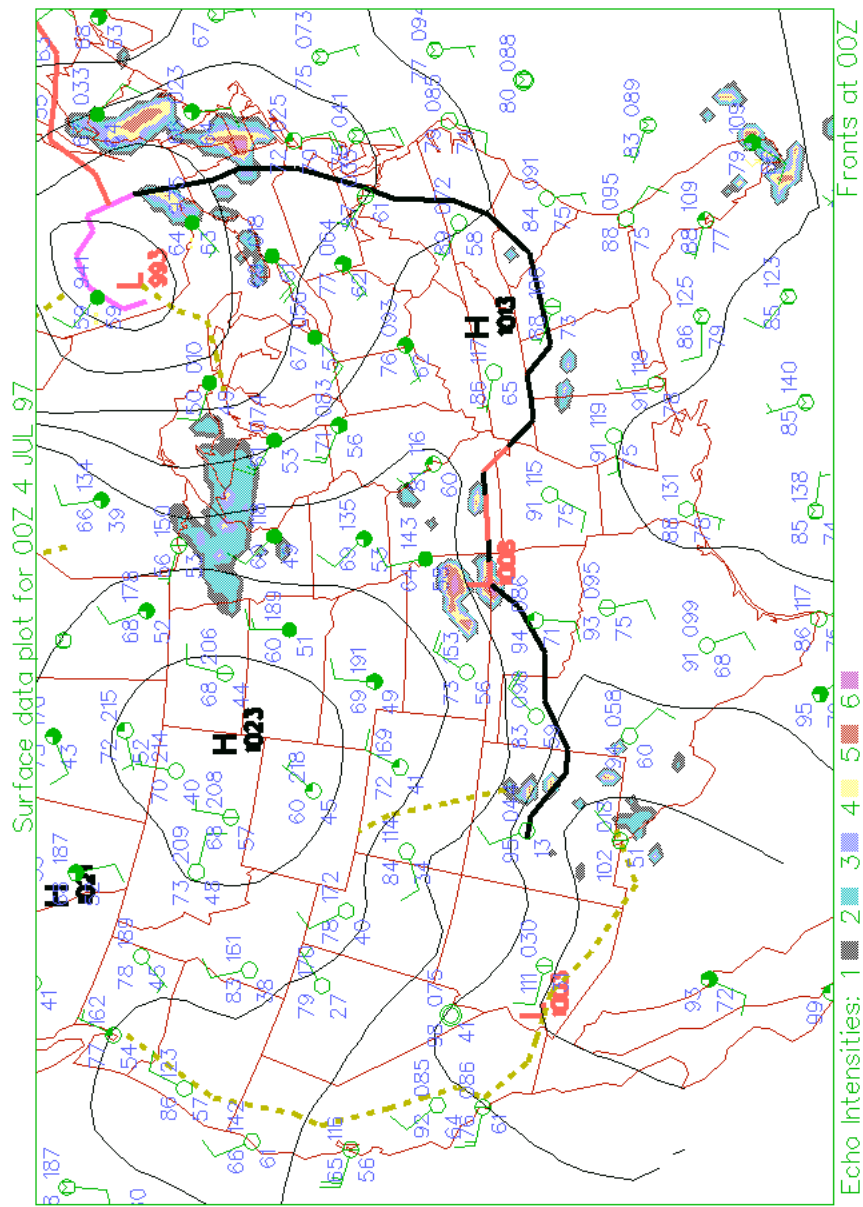


Figure 8: Synoptic map valid for 00Z 4 July 1997. Depicted are the surface observations, MSLP contours, frontal positions and radar precipitation intensities

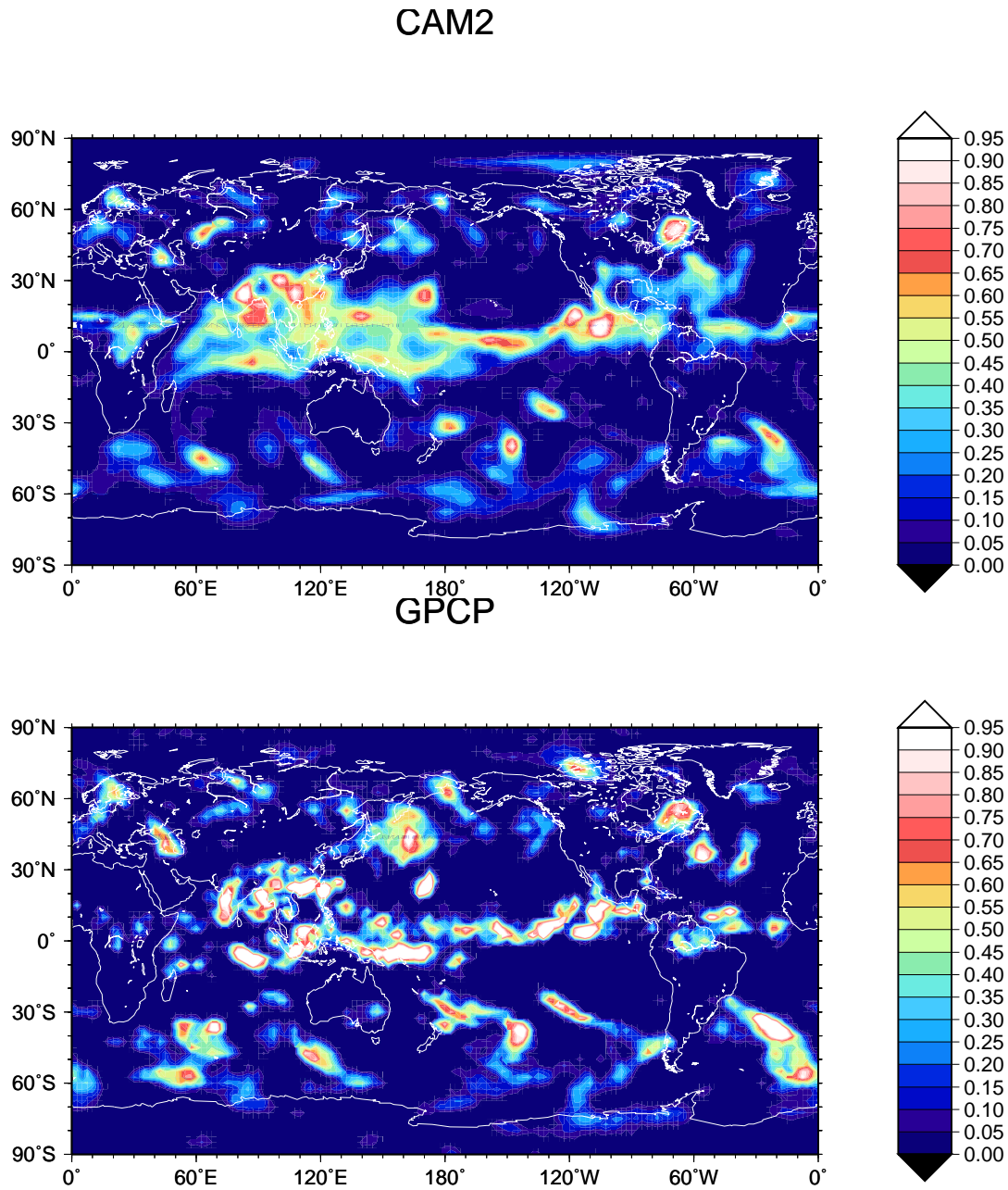


Figure 9: Comparison of the 24 hour model forecast (top) and daily GPCP (bottom) precipitation rate for 4 July 1997. Units in mm/day.

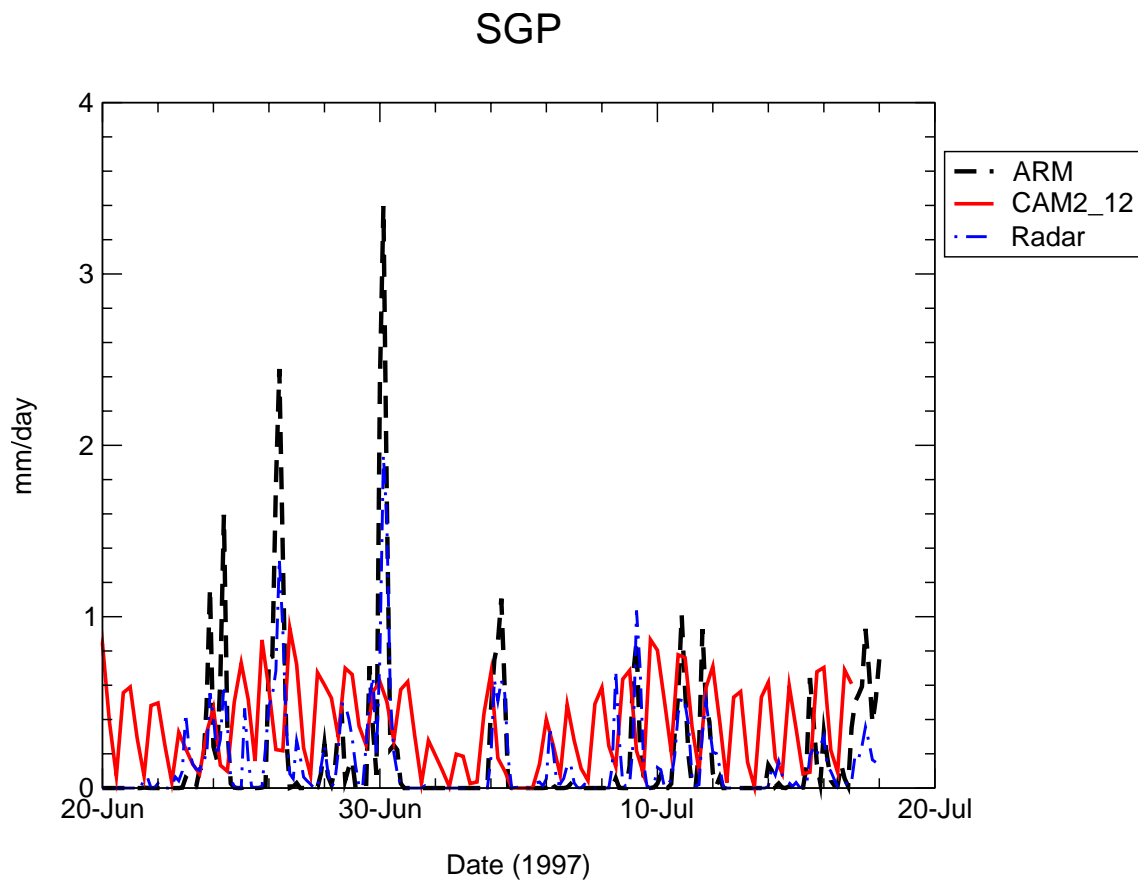


Figure 10: June/July 1997 IOP time series of precipitation for the SGP ARM observations (broken black line), the CAM 24h forecast rainfall averaged over the SGP domain (red), and radar estimates averaged over the region of the four CAM gridboxes indicated in Fig. 1 (dash-dot blue)

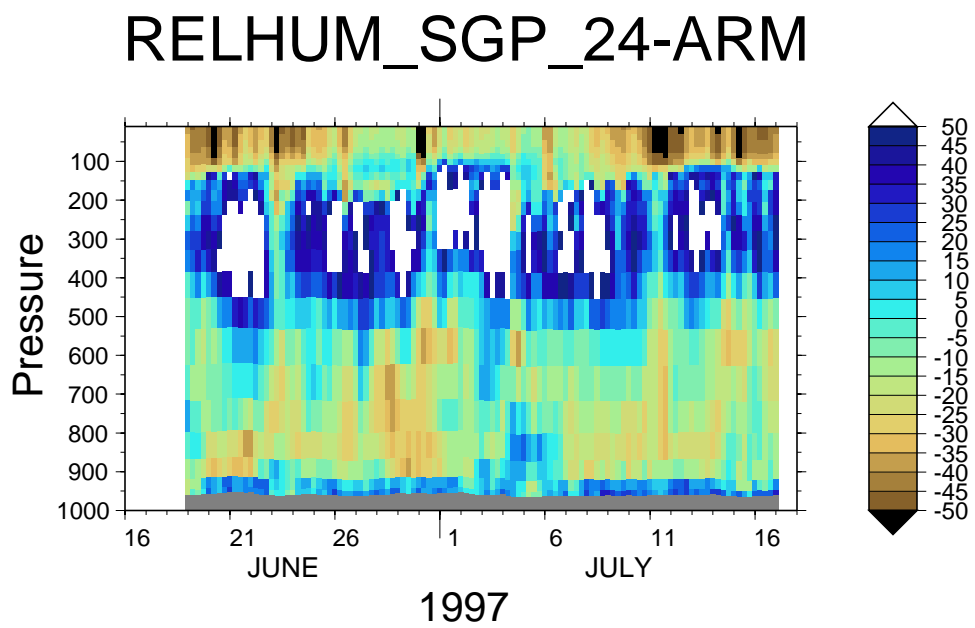


Figure 11: Differences in relative humidity (percent) at SGP site between ARM observations and 24 hour forecasts started every 6h for the June/July 1997 IOP

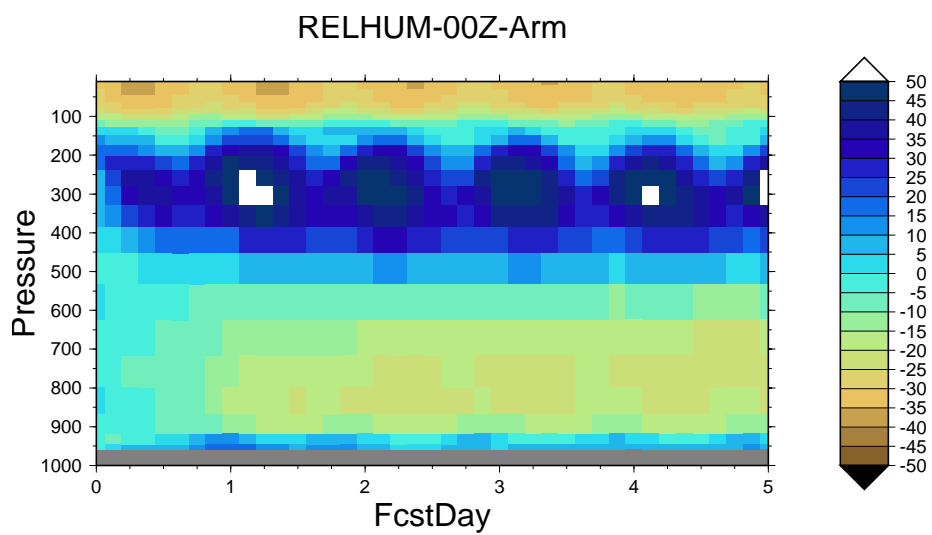


Figure 12: Mean differences in relative humidity at SGP site between ARM observations for 5 day forecasts started at 00Z for the June/July 1997 IOP

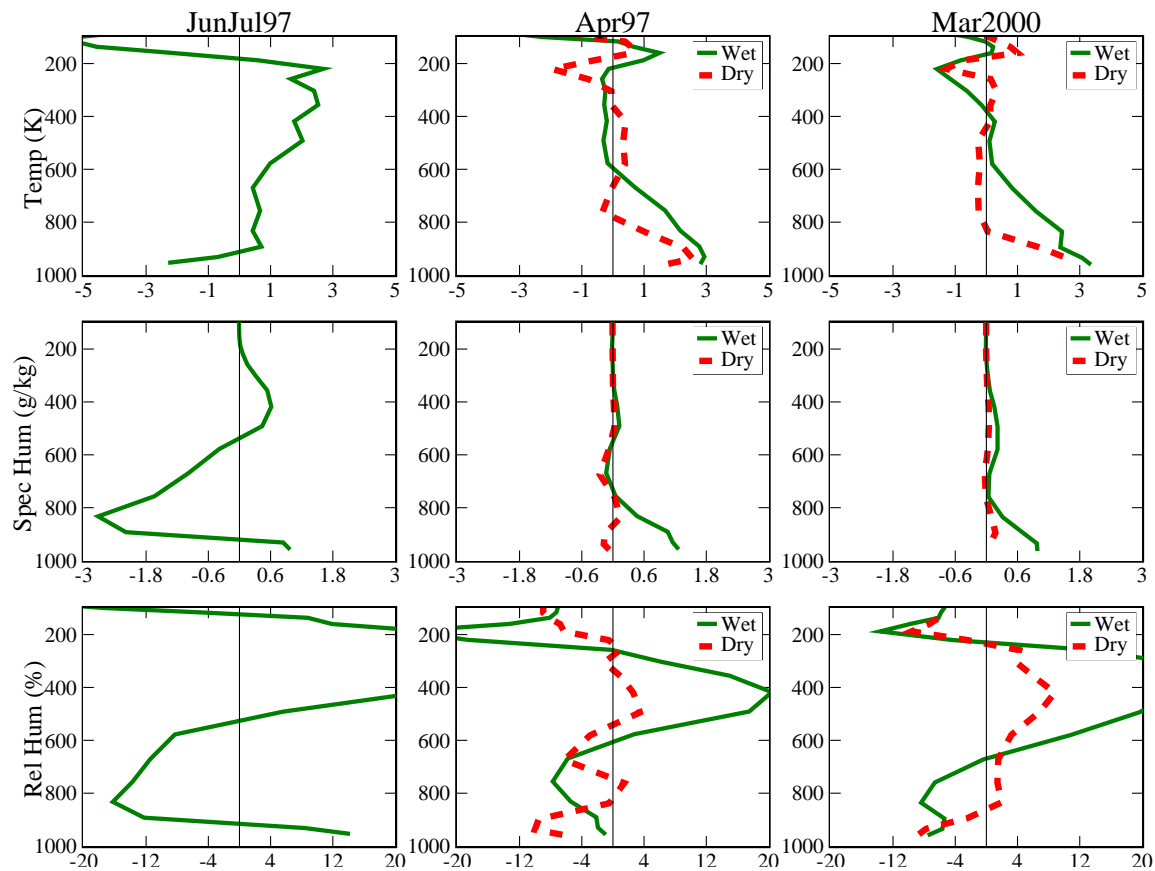


Figure 13: Differences between 24h forecasts and ARM observations at the SGP site for temperature(K), specific humidity(gm/kg) and relative humidity(percent) for the June/July 1997 IOP(left), the April 1997 IOP(center) and the March 2000(right) IOP. For the March and April IOPs differences for both the rain (green) and dry (red) subperiods are shown.

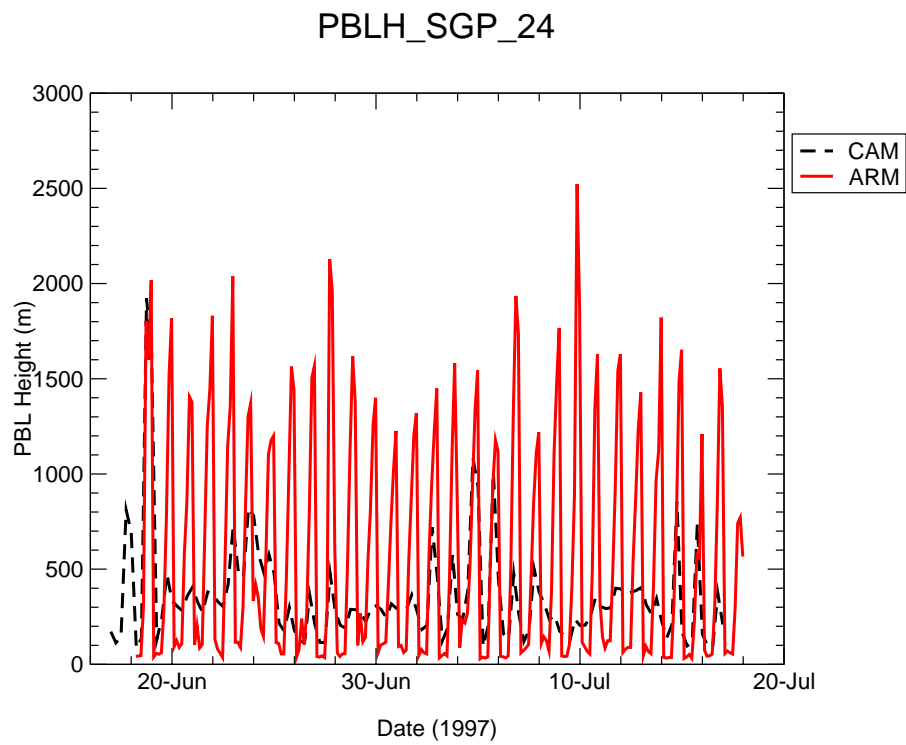


Figure 14: Comparison of PBL height estimated from ARM soundings and for 24 hour forecasts over the June/July 1997 IOP at the ARM SGP site.

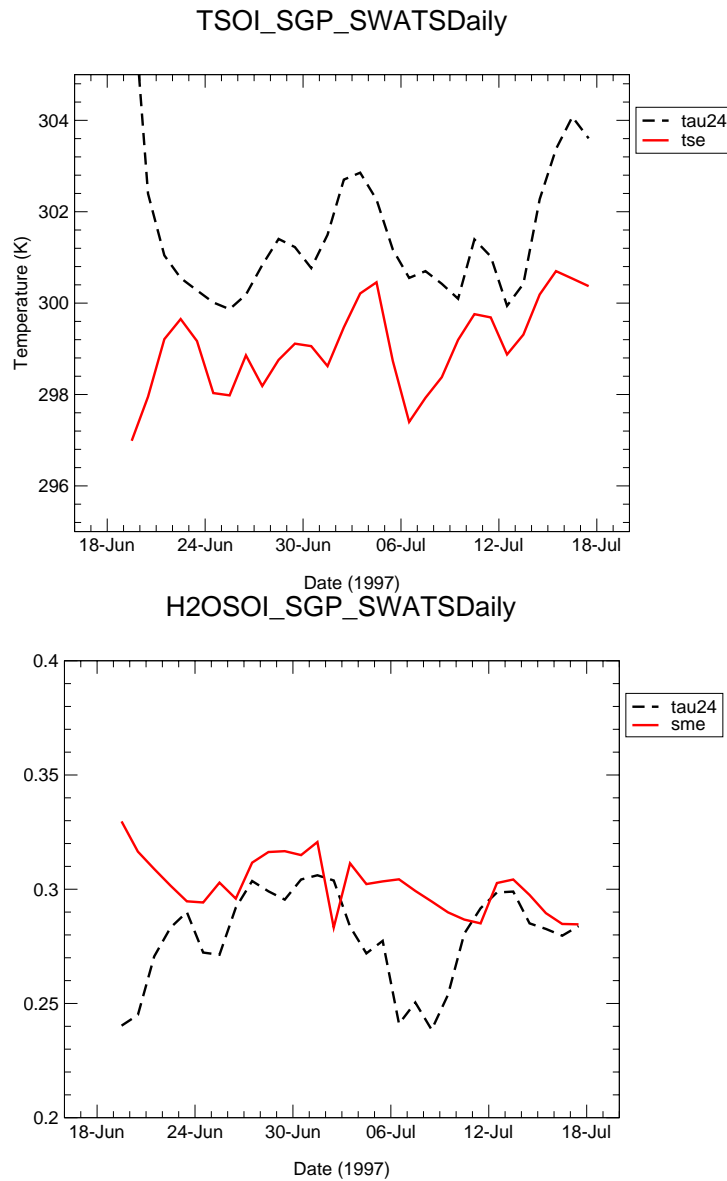


Figure 15: Temperature (K) (top) and volumetric soil water (mm³/mm³) (bottom) for the top layer of soil (6cm) for the SGP site for June/July 1997. Solid lines are 24 h forecasts, dashed lines are averages over all SWAT observation stations. The SWAT stations used are those indicated in Fig. 1.

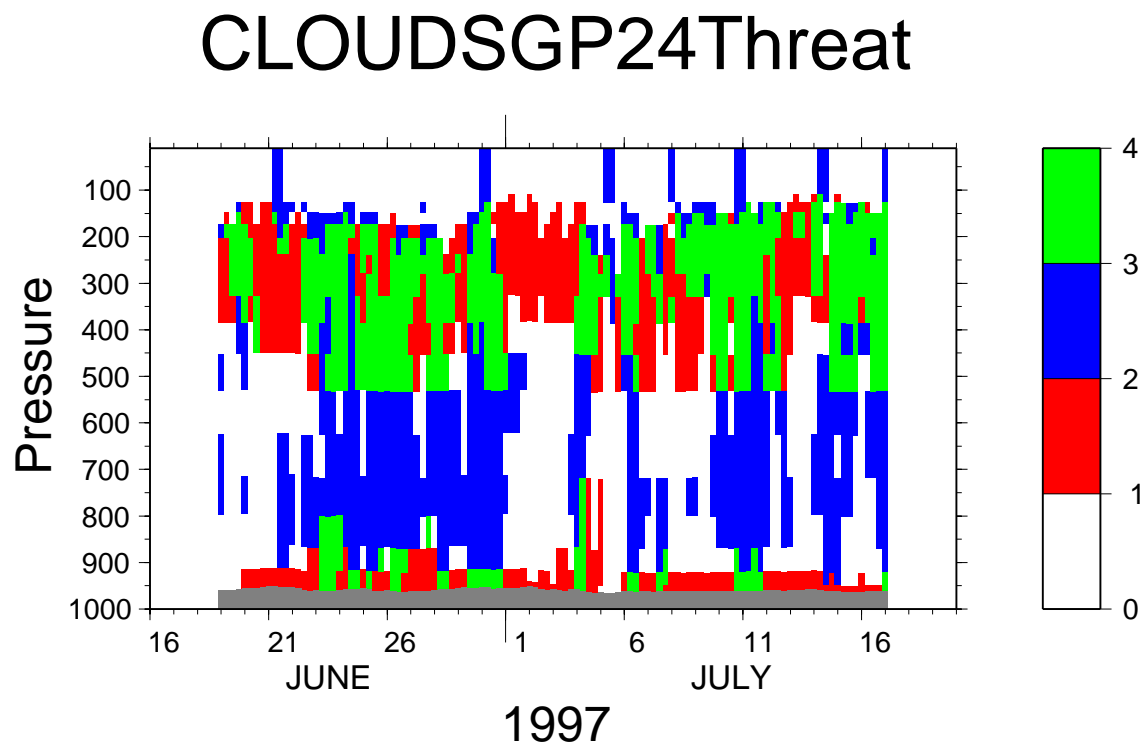


Figure 16: Comparison of the 24 hour model forecast of cloud and the ARSCL cloud hydrometeor estimates for the June/July 1997 IOP at the SGP site. Color code is explained in Table 4.

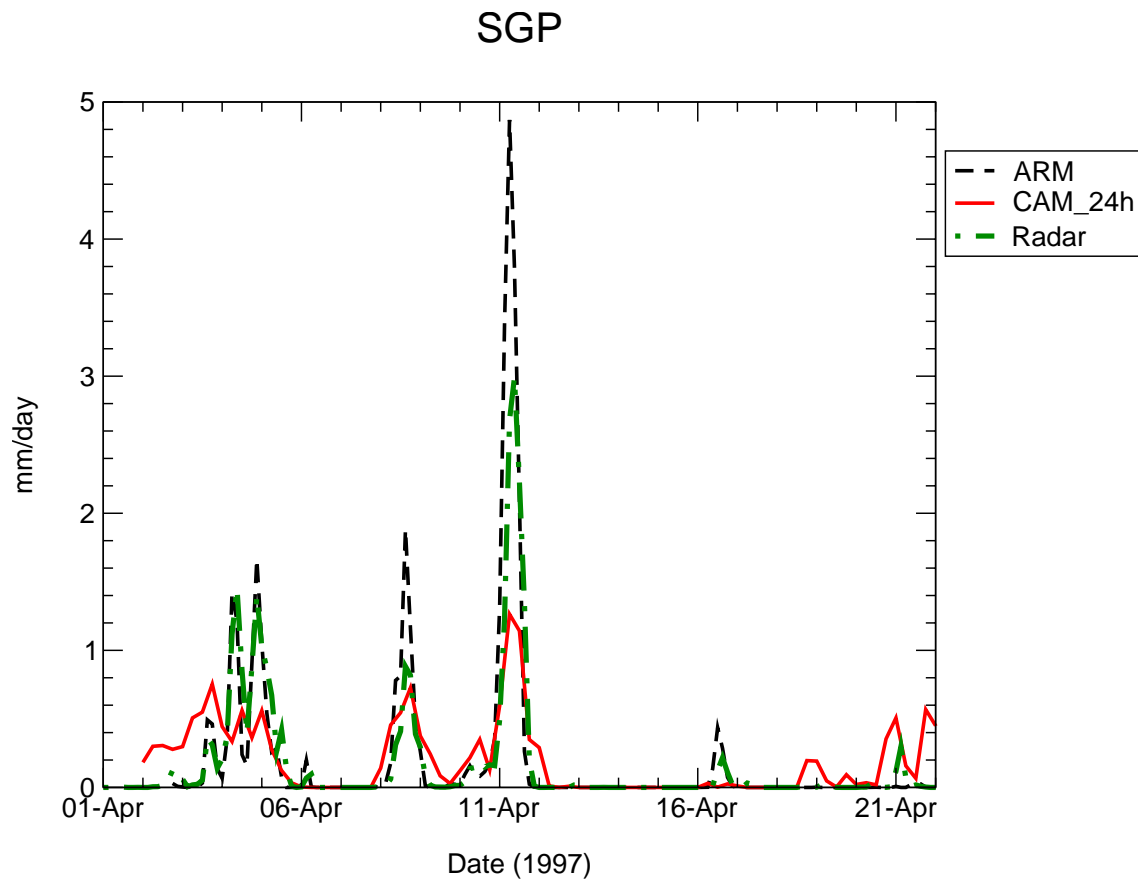


Figure 17: April 1997 IOP time series of precipitation for the SGP ARM site observations (dashed black), the CAM 24h forecast rainfall averaged over the SGP domain (solid red), and radar estimates for the region of the four CAM gridboxes indicated in Fig. 1 (dashed green).

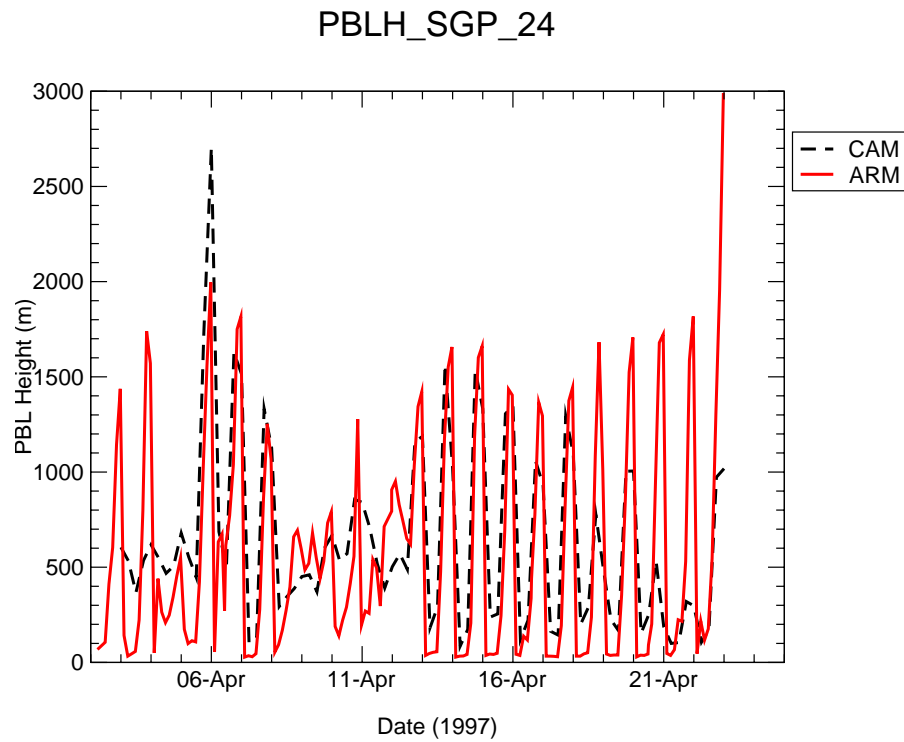


Figure 18: Comparison of PBL height estimated from ARM soundings and for 24 hour forecasts over the April 1997 IOP at the SGP site.

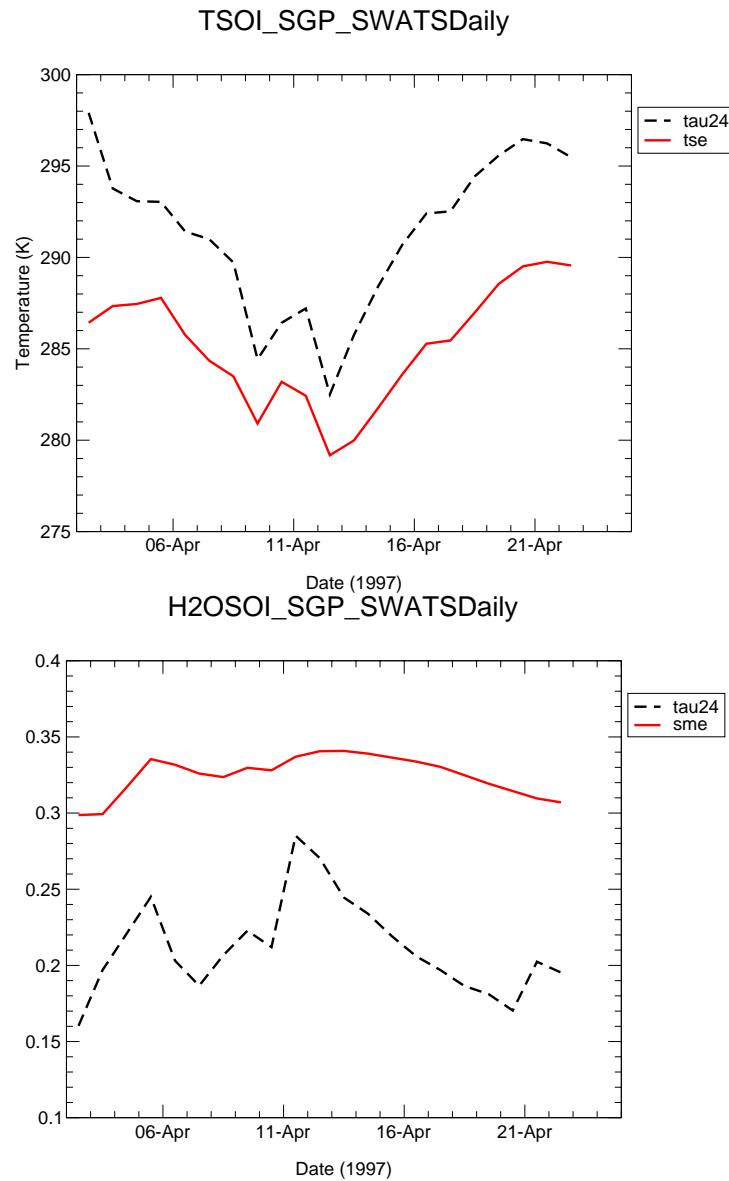


Figure 19: Temperature (K) (top) and volumetric soil water (mm³/mm³) for the top layer of soil (6cm) for the SGP site during April 1997. Solid lines are 24 h forecasts, dashed lines are averages of all SWAT station observations. The SWATS stations used are those indicated in Fig. 1.

CLOUDSGP24Threat

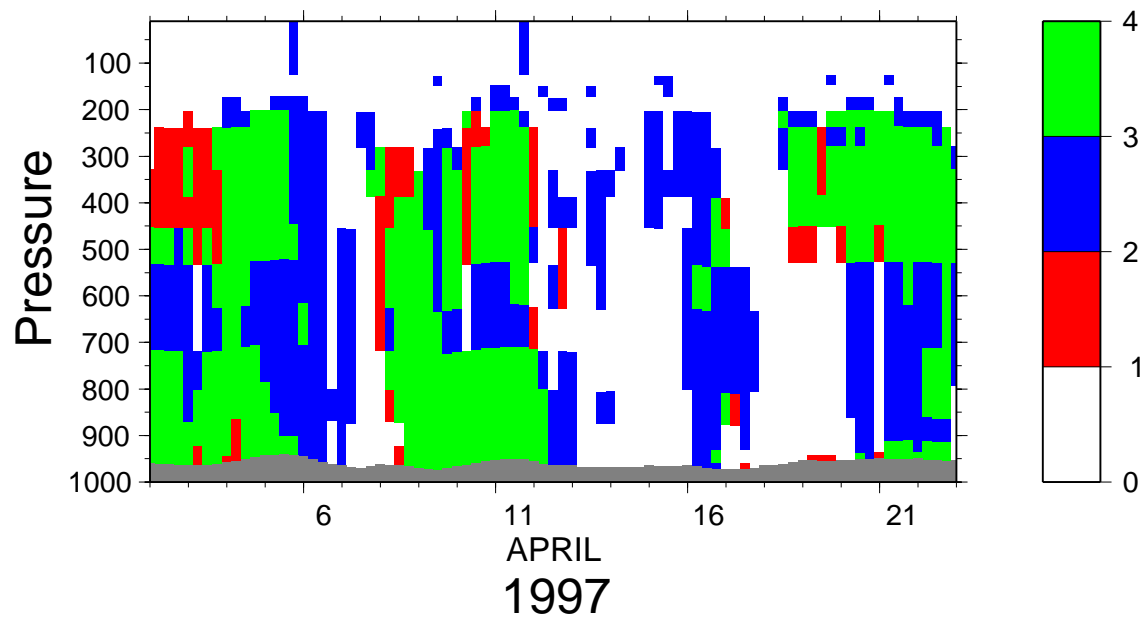


Figure 20: Comparison of the 24 hour model forecast of cloud and the ARSCL cloud hydrometeor estimates for the April 1997 IOP at the SGP site. Color code is explained in Table 4.

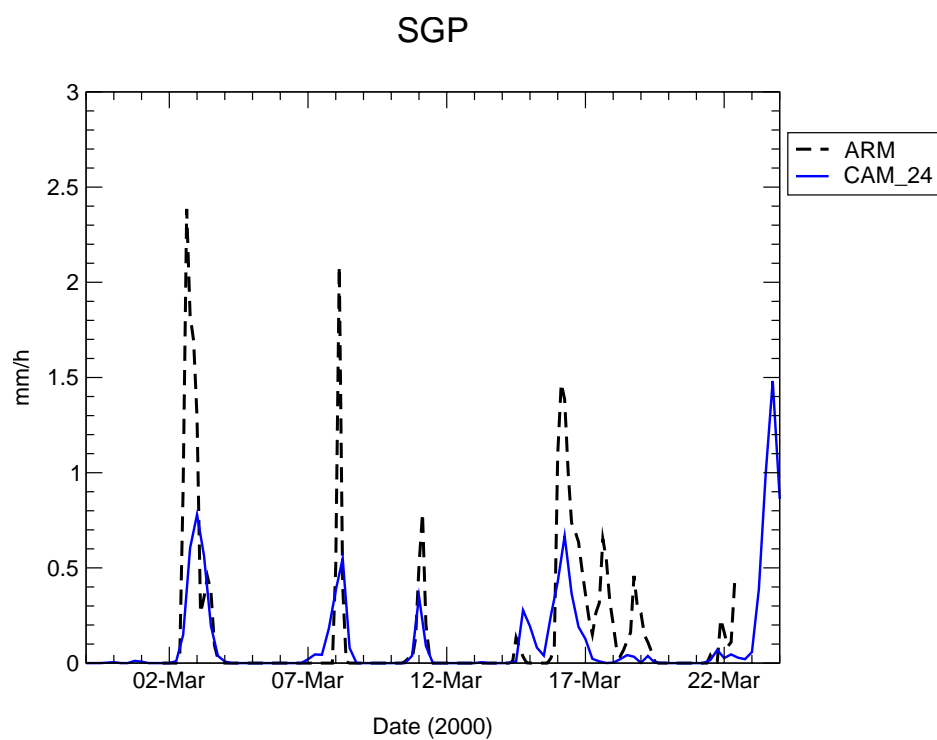


Figure 21: March 2000 IOP time series of precipitation for the SGP ARM site observations (dashed black), the CAM 24h forecast rainfall averaged over the SGP domain(solid red).

CLOUDSGP24Threat

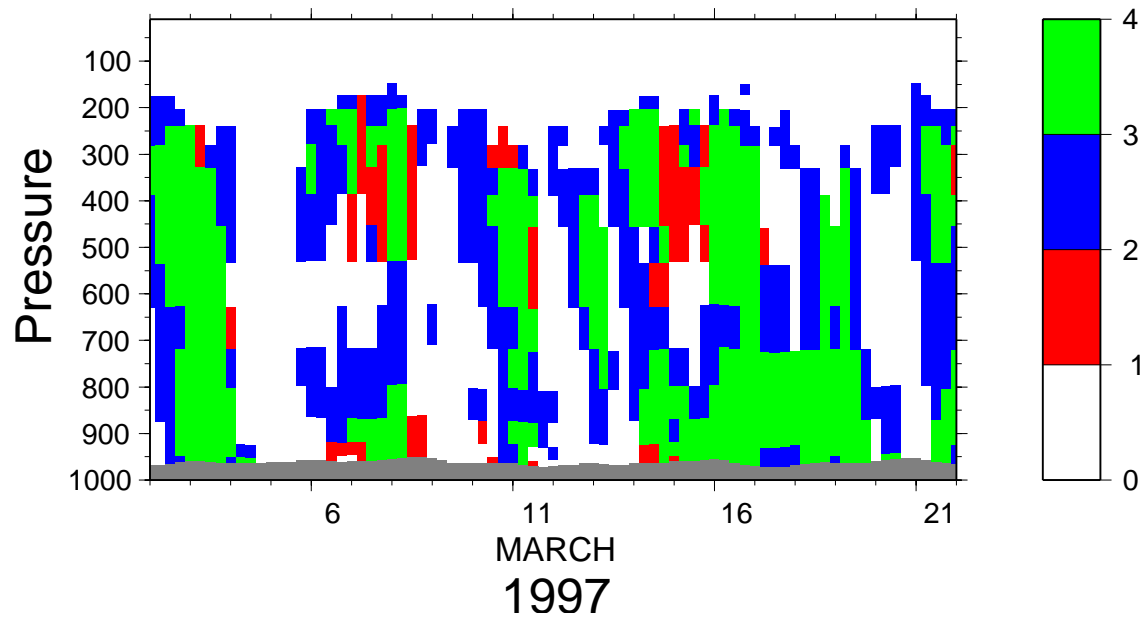


Figure 22: Comparison of the 24 hour model forecast of cloud and the ARSCL cloud hydrometeor estimates for the March 2000 IOP at the SGP site. Color code is explained in Table 4.

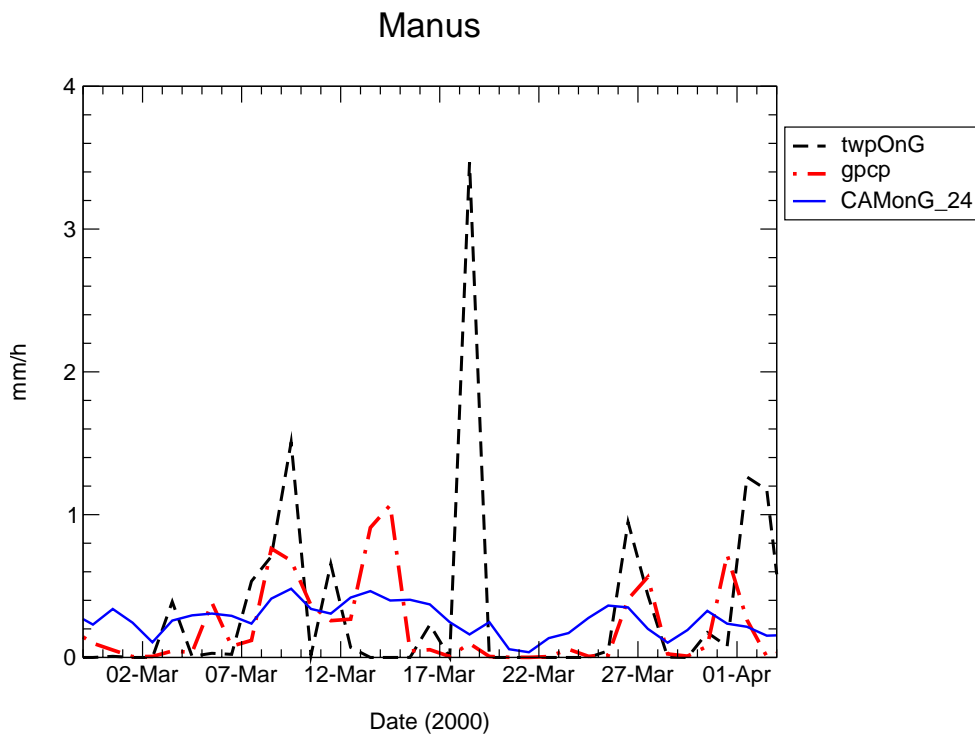


Figure 23: March 2000 IOP time series of precipitation for the ARM Manus observations (broken black line), the CAM 24h forecast, and GPCP estimates for the region (dash-dot blue)

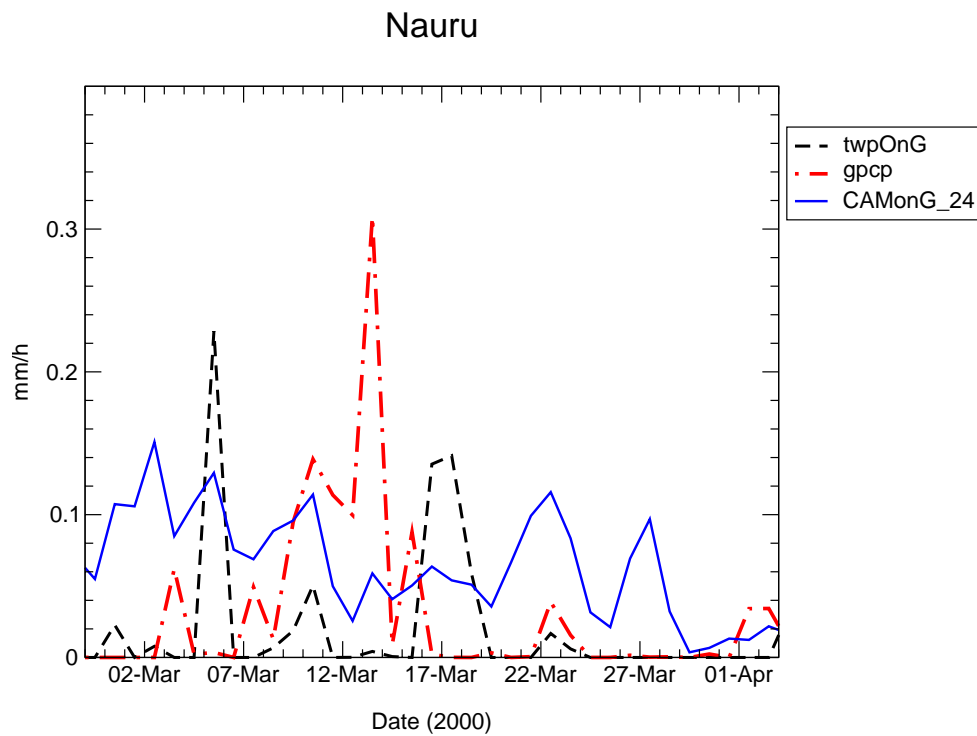


Figure 24: March 2000 IOP time series of precipitation for the ARM Nauru observations (broken black line), the CAM 24h forecast, and GPCP estimates for the region (dash-dot blue)

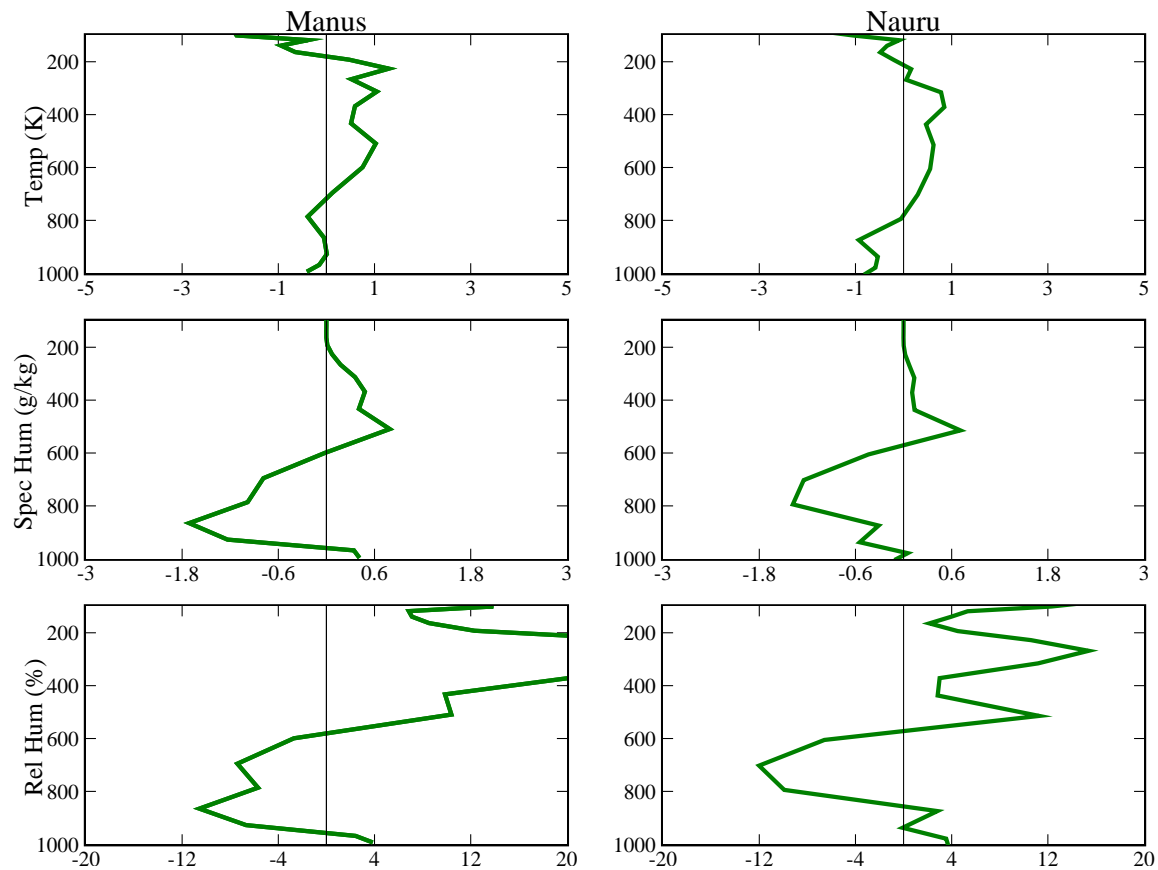


Figure 25: Mean differences between 24h forecasts and ARM observations at the ARM TWP sites Manus (left) and Nauru (right) for temperature (K) , specific humidity(gm/kg) and relative humidity(percent) during the March 2000 IOP.

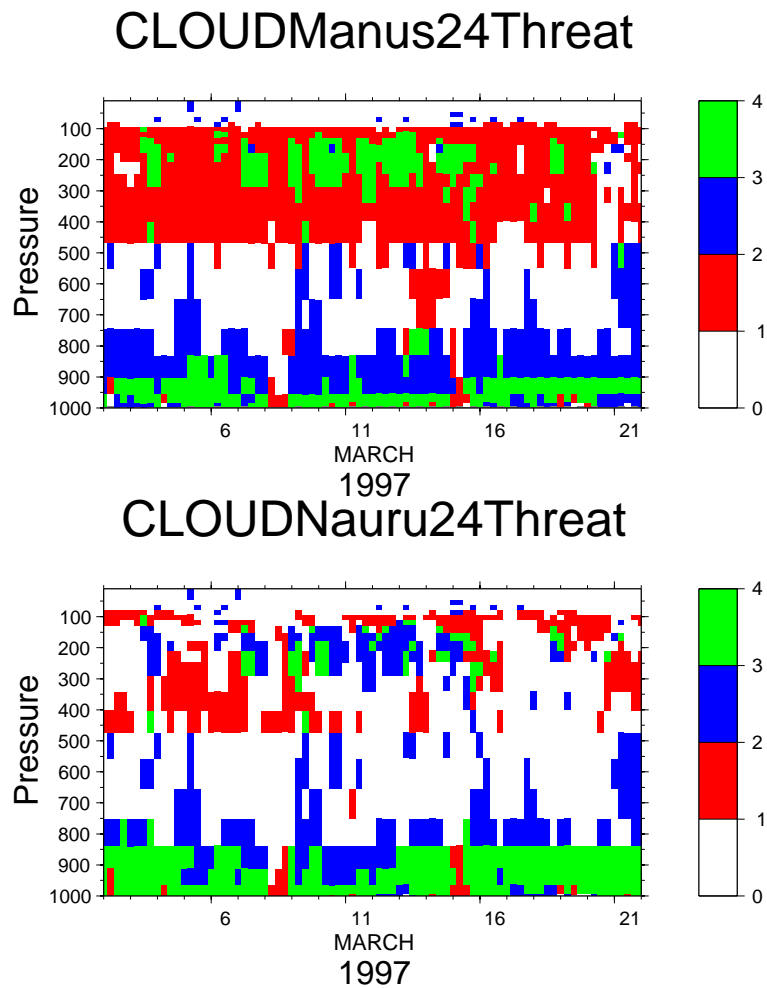


Figure 26: Comparison of the 24 hour model forecast of cloud and the ARSCL cloud hydrometeor estimates for the March 2000 IOP at the TWP sites, Manus (top) and Nauru(bottom). Color code is explained in Table 4.